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Report HPSR-1 (1980)

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16. ABSTRACT

This report is a collection of nine individual Health Physics Society subcommittee reports on different aspects of environmental radiation data associated with nuclear power plants. The subcommittee reports include: Environmental Radiation Monitoring Objectives, Definition of Critical Pathways and Radionuclides for Population Radiation Exposure at Nuclear Power Stations, Propagation of Uncertainties in Environmental Pathway Dose Models, Detection of Changes in Environmental Levels Due to Nuclear Power Plants, Quality Assurance for Environmental Monitoring Programs, Reporting of Environmental Radiation Measurements Data, Statistical Methods for Environmental Radiation Data Interpretation, Effective Communication with the Public, Environmental Radiological Surveillance–Mechanisms for Information Exchange.

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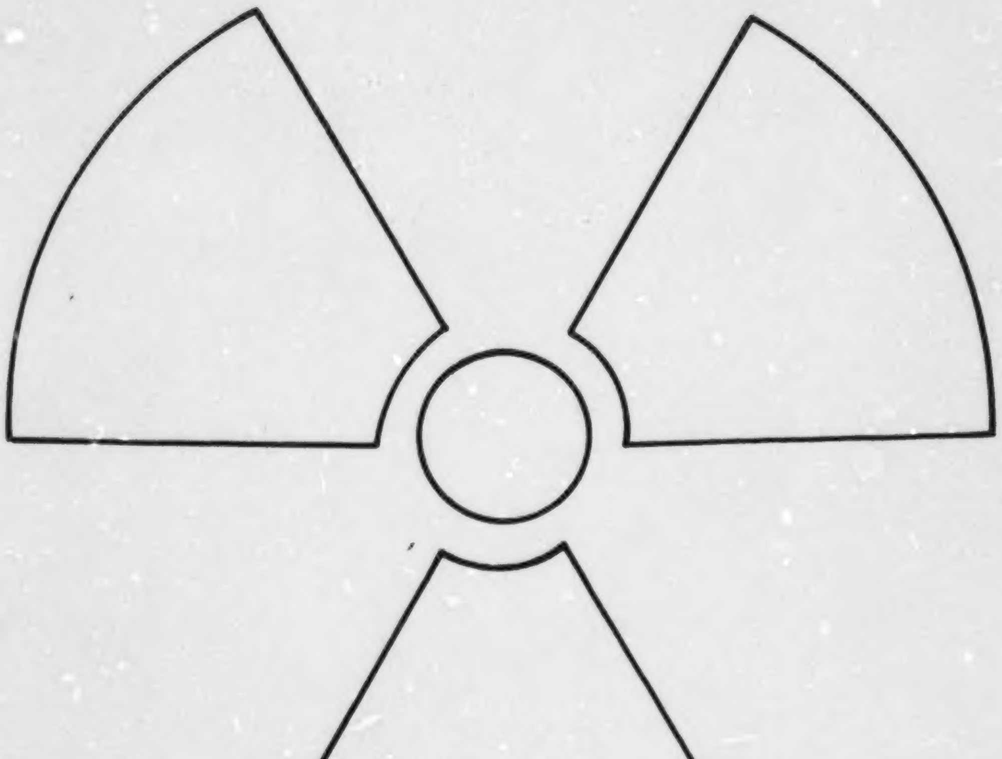

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Health Physics Society
Committee Report
HPSR-1 (1980)

J. E. Watson, Chairman

August 1980

Office of Radiation Programs
U.S. Environmental Protection Agency
Washington, D.C. 20460

Foreword

The Office of Radiation Programs (ORP) of the U.S. Environmental Protection Agency is responsible for monitoring the environment and for assessing the public health impact of radiation from all sources in the United States. To meet these responsibilities ORP's radiological dose assessment program relies heavily on environmental radiation data gathered by numerous organizations and laboratories across the country.

In the past decade, EPA has found that the poor technical quality of some radiation data has been a source of difficulty in its own program and a concern to other agencies, including the Nuclear Regulatory Commission, the Department of Energy, the Bureau of Radiological Health, and the National Bureau of Standards. For some years now, representatives from these agenices as well as from State agencies, universities, and private industry have discussed the problems and explored ways, in both business and professional forums, in which to improve the quality of environmental radiation data. The Environmental Protection Agency has encouraged its professional staff members to participate in such activities.

The Office of Radiation Programs has closely observed the activities of the Health Physics Society that led to the production of this report. Those activities are summarized in the Preface. The report represents the efforts of more than 75 radiation health professionals who, under the auspices of the Health Physics Society, have pooled their expertise to identify and solve some of the problems associated with the quality of environmental radiation data.

The Office of Radiation Programs is pleased to have the opportunity to fund the printing charges for the report in order to facilitate its wide distribution and use. The Office of Radiation Programs hasn't, however, assessed the technical validity of this report, and our support for printing it is not an endorsement of its contents. Readers are encouraged to direct their comments on this report to Dr. J. E. Watson, Chairman, Health Physics Society Ad Hoc Committee, Department of Environmental Sciences & Engineering, School of Public Health, Rosenau Building, University of North Carolina, Chapel Hill, North Carolina 27514.

Office of Radiation Programs
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UPGRADING ENVIRONMENTAL RADIATION DATA

REPORT OF HEALTH PHYSICS SOCIETY AD HOC COMMITTEE

J.E. Watson, Jr. (University of North Carolina), Chairman

Preface

The organization of the committee for Upgrading Environmental Radiation Data resulted from needs expressed at several conferences and workshops held over the past decade related to environmental radiation data.

An effort to bring together representatives from industries, universities, state governments and federal agencies to discuss and explore means to improve environmental radiation protection was initiated in 1967 in Atlanta, Ga. At the Symposium on Off-Site Public Health Aspects of Nuclear Power Plant Operation, sponsored by the U.S. Public Health Service, National Center for Radiological Health, and the Georgia Department of Public Health, technical presentations of good quality were made on environmental radiation surveillance which noted problems related to environmental radiation data.

Discussion and interchange of information was disappointing among participants of the 1971 Southern Conference on Environmental Radiation Protection for Nuclear Plants in St. Petersburg, Fl. The conference was organized and sponsored by the U.S. Environmental Protection Agency (EPA) and the Florida Division of Health with the cooperation of the Florida Power Corporation.

A June 1974 seminar and March 1976 workshop both, however, had positive impacts and served as a direct impetus to the organization of this committee. The Southeastern Seminar on Environmental Radiation Surveillance was held in 1974 in Columbia, S.C., under the sponsorship of EPA and the South Carolina Department of Health and Environmental Control. The 1976 Southeastern Workshop on the Utilization and Interpretation of Environmental Radiation Data in Orlando, Fla., was organized by the Florida Department of Health and Rehabilitative Services and the University of Florida in collaboration with the Nuclear Regulatory Commission and EPA.

The proceedings of the 1976 workshop, moderated by Melvin W. Carter, included the following summary:

"The objectives of the workshop were to make presentations and provide for open and candid discussion on the proper purposes for environmental surveillance programs; data requirements and the development of baselines; and utilization and interpretation of data.

Some of the primary issues raised included:

The quality and usability of existing data

The need for different objectives for different monitoring programs

The feasibility of establishing common definitions of what constitutes critical pathways and model verification

What constitutes an optimum blend of monitoring and modeling

The advisability and feasibility of generating data requirements for regional impact assessments of multiple nuclear facilities

Methods to determine if a detected increase in radiation levels is "real" and whether it is due to plant operations

Methods to convert data to individual and population dose commitments

More standardization in data reporting conventions, including the definitions of detection limits and the treatment of results at or below these limits

Methods of reporting data for general public understanding

Improving the Quality Assurance of the entire program including sampling

The meeting provided a mechanism for scoping of problems and identification of various approaches to their solution. One of the most striking and significant elements during the entire workshop was the willingness of the representatives from industry, governmental agencies and academic institutions to freely exchange information and opinions, thus establishing communication which lays the groundwork for mutual cooperation in solving the pressing and complex environmental radiation data problems confronting the Health Physics Profession."

Communications among the participants of the 1976 workshop had improved significantly compared with the 1971 conference. This workshop indicated that most organizations were having similar problems in making meaningful use of environmental radiation data. Specific problems related to the quality and utilization of data were identified and emphasized. Many of these problems had been identified as early as the 1967 symposium but still lacked solutions. The demonstrated willingness of representatives from industries, universities and government agencies to exchange information and opinions layed the ground work for cooperation in solving the problems identified at the workshop.

Following the 1976 workshop, H. Richard Payne proposed the formation of a multi-organizational project to pursue solutions to the problems identified in the quality and utilization of environmental radiation data. The proposed project was discussed with persons who had participated in the 1976 workshop and with other representatives of organizations involved in environmental radiation activities. There was an overwhelming concensus of opinion that the project should be pursued and there was an encouraging willingness of persons contacted to participate in the project.

An organizational meeting was held in the spring of 1977. Committee officers selected by participants were: Chairman - James E. Watson, Jr.; Vice-chairman - Enrico F. Conti; and Secretary - H. Richard Payne. Committee members are listed following this preface. At that meeting it was decided that the Health Physics Society should be requested to serve as sponsor for the project. John A. Auxier participated in the organization of this project and carried the participant's request for sponsorship to the HPS's Board of Directors. The Board approved sponsorship of the Ad Hoc Committee for Upgrading Environmental Radiation Data in July 1977.

Based upon the needs identified at the Orlando workshop and other needs identified by committee participants, nine project objectives were assigned top priority by the committee. These project objectives are the topics included in this report. The committee provided overall coordination and direction of the project. A project manager, from the committee, was established for each objective and a subcommittee was formed to pursue solutions to the problems posed by the objective. Project managers selected subcommittee members from the most qualified persons available from organizations represented on the committee and from other organizations. This provided very broad national participation in this project. Subcommittee members are listed at the beginning of each section of this report. The project manager had the option of serving as subcommittee chairperson or appointing the chairperson.

The results of the committee's work were presented at a special session of the HPS's Annual Meeting in Philadelphia on July 12, 1979. This special session was made possible through the excellent cooperation of the HPS Program Committee, James E. McLaughlin, Jr., Chairman.

This report was finalized following the HPS's Annual Meeting. It is an HPS committee report and as such was not reviewed and approved by the Society's Board of Directors. Committee approval of subcommittee reports was based upon a favorable vote by a simple majority of committee members with the understanding that dissenting opinions would be presented in the report preface. The following dissenting opinions were prepared by H.L. Volchok:

> Chapter 4, p 4-2, In reference to section "Effects of Effluents from Coal-Fired Stations": Recent published studies indicate that while the radioactivity associated with effluents from coal-fired power plants is not insignificant, the proximity to a nuclear power plant and the differences in radionuclides involved should preclude misidentification.
>
> Chapter 4, p 4-6, In reference to section "Conclusions", item 4 e: Attempts to standardize analytical and sampling procedures are often counterproductive and tend to stifle responsibility and improvisation. We would emphasize improving but not standardizing.
>
> Chapter 6, p 6-4 , In reference to section "Exponential Notation": In direct opposition to the position outlined, several participants contend that (a) rarely are investigators faced with results beyond the 36 order of magnitude range of the prefixes, and (b) computational mistakes are not minimized by use of exponents; the reverse is often the case. For the three examples given, the dissidents strongly recommend:

$$2810\ \mathrm{pCi\cdot L^{-1}} = 104\mathrm{Bq\cdot L^{-1}}$$

$$12\ \mathrm{uR\cdot h^{-1}} = 3.1\ \mathrm{nC\cdot Kg^{-1}\cdot h^{-1}}$$

$$123\ \mathrm{mrad} = 1.23\ \mathrm{mGy}$$

It should be emphasized that this report is the collection of nine individual subcommittee reports. The report is not intended to be a completely integrated and comprehensive guide for environmental radiation surveillance. Efforts were made to avoid contradictions within this report, but some overlaps and omissions are to be expected. This document is intended to report on work to resolve long standing problems in the quality and utilization of environmental radiation data. As previously stated, the report contains the results of nine project objectives assigned top priority by the committee. From its conception the committee recognized that consideration of the broad spectrum of all types of environmental radiation data was ideal. However, in a number of cases this was not feasible, and it was necessary for subcommittees to limit their treatment to environmental radiation data associated with nuclear power plants. The committee recognizes that this report will not be the final answer to all problems and that efforts in the future will be needed to continue to upgrade the quality and utilization of environmental radiation data. The committee believes that the continuation of this effort is an appropriate task for one of the new sections to be organized within the Health Physics Society.

Subcommittee manuscripts were prepared in accordance with directions developed by the National Bureau of Standards. The report was published as a Health Physics Society Committee Report by the Office of Radiation Programs, U.S.

Environmental Protection Agency. The committee is indebted to Raymond H. Johnson, Jr. for his coordination of the report's publication. The committee requested support from the HPS for funds to help pay for the preparation and distribution of the report. The HPS's Board responded generously to this request. The support and encouragement by Board members of this committee's efforts are gratefully acknowledged.

A special acknowledgement is made to committee member Herbert L. Volchok. He served as the committee "whip" -- encouraging project managers and subcommittee chairpersons to comply with schedules established by the committee. Appreciation is also extended to the committee chairman's secretary, Frances L. Dancy. She efficiently assisted in administrative matters, handled a multitude of committee correspondence and prepared a large portion of the final report manuscript for publication.

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ENVIRONMENTAL RADIATION MONITORING OBJECTIVES

E.F. Conti (Nuclear Regulatory Commission, Washington, DC), R.H. Johnson, Jr. (Environmental Protection Agency, Washington, DC), D.E. McCurdy (Yankee Atomic Electric Co., Westborough, Mass.), J.A. McLaughlin (Department of Energy, Environmental Measurements Laboratory, New York, NY) and C.A. Pelletier (Science Applications, Inc., Rockville, MD)

The lack of specific guidance for environmental monitoring has confused the objectives of different programs and affected the quality and usefulness of results. Beginning with the general principles stated by the ICRP in 1965, and by other authoritative groups, a viewpoint on objectives was developed to aid our understanding of the potential and limitations of three types of monitoring. Excluded from explicit consideration are monitoring for accidents, basic environmental research and geological surveys. The purposes of monitoring, which relate to assessing risk to man, are to facilitate the assessment of dose to man and the assessment of changes in the radiation environment. The emphasis depends on the type of monitoring identified. The three types are ambient, i.e., regional or global monitoring; facility monitoring and special investigations that are mainly retrospective studies such as those needed for decommissioning. The workgroup noted that technical limitations in measurement and calculation also lead to a diminished and sometimes inadequate data quality. This is a significant problem when measurements are performed near the lower limit of detection and the pre-existing radiation field and contributions to concentration and dose from any undesirable dispersed radionuclides cannot be quantified. The workgroup identified particular limitations for each of the three types of monitoring related to consideration of the stated objectives.

(Environmental; limitations; monitoring; objectives)

Introduction

The Health Physics Society Committee on Upgrading Environmental Radiation Data identified the need for an evaluation of the objectives of environmental monitoring. Representatives of regulatory, developmental, commercial, State, and utility organizations comprised the work group. Monitoring objectives were identified in publications, and examples were developed on how these objectives are reflected in different types of monitoring programs. The work group emphasized routine environmental monitoring as opposed to the objectives related to accidental releases of radioactive material to the environment. However, some of the considerations of this report would be of value in an evaluation of accidental releases of radioactive material to the environment. The limitations of monitoring programs related to objectives were evaluated.

Background

The broad objectives of environmental monitoring programs identified by the International Commission on Radiological Protection[1] were:

a. The assessment of the actual or potential exposure of man to radioactive materials or radiation present in his environment or the estimation of the probable upper limits of such exposure.

b. Scientific investigation, sometimes related to the assessment of exposures, sometimes to other objectives, e.g., the general characterization of the radiation environment, and

c. Improved public relations.

In 1972, the Environmental Protection Agency identified three similar objectives but in a somewhat more specific manner[2].

Despite these objectives, routine environmental monitoring programs conducted at nuclear facilities by facility operators, government organizations, and research laboratories continued to consist mostly of collecting environmental samples and conducting analyses for gross or total alpha, beta, and gamma radioactivity.

In the past few years, both the types of environmental samples collected and the analyses performed have been focused more on dose-to-man considerations. Environmental media representing pathways of exposure to man by specific radionuclides are now often collected to allow correlating environmental radioactivity concentrations to accepted dose values[3,4].

Programs of ambient or regional monitoring, facility operation, and special studies were examined by the work group. This examination indicated that a number of objectives, not all complementary, are used for the organization and operation of these programs. The objectives stated by the operators of specific programs have included assessment of adequacy of facility controls, assessment of dose, demonstration of compliance with regulations, detection of long-term trends, protection of the general public, public acceptance, detection of environmental pathways, emergency response, and offsite versus onsite source delineation. For many reactor facilities, effluent releases have been markedly reduced in the last decade, but environmental monitoring programs are still required[5] as a means of continuing the assessment of the environmental impact of facility operation. Several site-specific studies on effluent and environmental field measurement have demonstrated the difficulty of unambiguously correlating the environmental radioactivity concentration of a radionuclide like radioiodine with the release of nuclear power plant effluents. A presentation of the objectives for the conduct of nuclear facility environmental monitoring programs was issued by the NRC in 1978.[6]

Nuclide-specific environmental measurements require that programs be conducted in a framework that relates the results to some environmental transport model and the resultant dose to man. Environmental radiological monitoring thus needs to be designed and operated in a manner that allows the environmental dose rate and radioactivity concentration to be used in meaningful estimates of potential dose to man.

Basic Purpose of Environmental Radiation Monitoring

The basic purpose of environmental radiation monitoring is to assess dose or estimate the risk to an individual or a population that may be exposed to radiation and radioactivity in the environment. The risk estimated need not be absolute but can be comparative in nature, i.e., the measured or calculated dose can be compared with background or the estimated risk compared to acceptable values.

This underlying purpose is expressed by one or more of the following specific objectives:

a. To aid in or assess dose,

b. To determine any trends of environmental radiation dose rates and radioactivity concentrations, and

c. To reassure members of the public and governmental organizations.

In addition to monitoring programs performed for primarily technical reasons, e.g., to assess dose or trends in environmental levels, public reassurance requires monitoring approaches that are responsive to the general public's perception of risk. This latter approach may be different from the first two, since public reassurance is related to perception of risk that is variable and difficult to quantify.

However, the underlying purpose of any environmental radiation monitoring is to aid in estimating risk that may result from exposures of the general public. The other monitoring objectives stem from this purpose.

Types of Programs

The basic objectives for environmental radiation monitoring are interpreted in a variety of programs in terms of program design, implementation, and use of monitoring data. Three types of programs (regional, facility, and special studies) were considered to indicate how the basic objectives are reflected in each program.

Regional Monitoring

An example of an ambient (regional) monitoring program is the Environmental Radiation Ambient Monitoring System (ERAMS).[7] This system is composed of nationwide sampling stations that provide air, surface and drinking water, and milk samples from which environmental radiation levels are derived.

The objectives of the ERAMS program are:

a. To provide data for developing a national dose model.

b. To provide a direct assessment of the population intake of significant radioactive pollutants.

c. To monitor pathways for significant population exposure from routine and accidental releases from major sources.

d. To estimate ambient levels of radioactive pollutants for standard-setting activities, verification of abatement processes, and identification of trends in the accumulation of long-lived radionuclides in the environment.

e. To provide an "early warning" system for emergency abatement actions or to indicate the necessity for further evaluation in the form of contingency sampling operations.

Design of Program - ERAMS is designed to accomplish stated objectives by providing baseline and long-term trend data for major airsheds, watersheds, and milk-producing regions. This system therefore complements localized facility programs conducted by State agencies and facility operators. ERAMS objectives are met by the selection of sampling stations to provide the best combination of radiation source monitoring (such as surface waters downstream from nuclear power reactors) and wide population coverage.

Implementation of Program - ERAMS objectives are implemented through several programs that provide coverage for particular exposure pathways or media and for particular radionuclides. These programs include collection of air particulates on filters that are analyzed for gross beta activity and for gamma emitters. Precipitation samples are also collected. The water program includes collection of surface water located downstream from nuclear facilities or at background locations. Grab samples for drinking water are taken at major population centers and selected nuclear facility environs. Pasteurized milk is also collected at one or more collection sites in each State.

Use and Interpretation of Data - ERAMS data are available quarterly in the publication entitled "Environmental Radiation Data". These data are not interpreted and are provided mainly for use by health professionals in State programs that cooperate in collecting ERAMS samples. Trend evaluations are prepared annually and published in "Radiological Quality of the Environment in the United States". Special dose assessments have been made to determine public health significance of fallout from atmospheric nuclear weapons test. Public reassurance with regard to fallout is provided by the identified reports and through official news releases during periods of fallout incidents.

Nuclear Facility Monitoring

Environmental monitoring programs are conducted during the operational lifetime of nuclear facilities primarily to meet the three basic objectives: determination of dose, assessment of trends, and public reassurance.

Design of Program - Programs that are conducted for routine facility operations are designed to accomplish the above-stated objectives by providing data (a) on dose rates and radionuclide concentrations for the important exposure pathways and (b) for detecting and assessing trends in environmental levels and concentrations of radionuclides that may contribute to human exposure. The public reassurance objective is accomplished, in part, by a demonstration of the quality of the environmental measurements.

Implementation of Program - As noted above, environmental sampling is implemented around nuclear facilities according to the most important exposure pathways. NRC has published a listing of typical features of environmental monitoring programs for nuclear facilities, including nuclear power reactors, uranium mills, and fuel fabrication facilities[6]. The program features include number of samples and locations, sampling and collection frequency, type and frequency of analyses, and collection and analysis of data from key locations as well as from an unaffected "control" location.

Special Studies

Introduction - A type of monitoring that is not easily classified as to technical purpose includes investigations of fairly localized environmental radioactivity that may produce unwanted radiation exposure to man. Basic environmental research and development, as well as efforts for geological surveys[8,9] are not included in this discussion of special studies.

Natural radioactive material is perturbed by mining and milling and is often redistributed in man's environment as waste material [10,11]. Nuclides left by a nuclear operation may be added to the same nuclides that were widely deposited from worldwide nuclear weapons debris[12] thus compounding the difficulty of measurement.

These programs are conducted to define contaminated areas by determining radionuclide concentrations and distributions and external radiation levels.

The objectives for this program are:

a. To respond to public concern.

b. To provide guidance for needed decontamination and to facilitate decommissioning.

Unlike the operational monitoring performed at nuclear facilities and regional or global monitoring, this monitoring is often performed retrospectively, i.e., after the discovery of the possibility of abnormal radioactivity where it previously was not expected, and it is usually performed for definite or relatively short periods of time.

Types of Special Studies for Decontamination and/or Decommissioning - The characterization of potentially contaminated areas is required for systematic dose assessment to aid either in estimating the risk to human inhabitants or in simply determining that the radiation parameters, e.g., concentrations and dose, are within an acceptable standard.* If the characterization indicates unacceptable conditions, it provides guidance for any cleanup effort, including protection of workers during decontamination, and helps to ensure that cleanup is effective and economical. In some instances, property is to remain within the administrative control of the owner or user of the property but will be used for an alternative purpose. In other instances, the property will revert to a new administrative control that will involve no use of radioactive material.

The type and extent of monitoring depends on whether or not only the first instance or whether both instances need to be addressed and whether decontamination is necessary. Since the criteria for each instance, as well as the numerical limits on radioactivity or radiation quantity, may differ, the details of the required monitoring may also differ.

There are two levels of survey. The first-level survey is an evaluation of the extent of radionuclide contamination and may include dose assessment. This survey is made primarily to identify places that may need decontamination. It makes little sense to perform full-fledged studies of areas that obviously will require decontamination and then to repeat a detailed final survey. For example, for a study of a large area of land, such as that of Enewetok Atoll[13], an airborne survey helps to determine the extent of the decontamination necessary. Then, ground-level evaluations are made in selected areas for detailed evaluations leading to dose assessment. An example of the first-level survey is the work of Leggett et al. for the Department of Energy's Remedial Action Program[14]. Following decontamination, a complete survey of record is necessary.

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*In the United States, there is no general accepted standard.

In cases that involve variable environmental levels, e.g., radon and its daughters in land and inside structures contaminated with radium, characterizing the area depends on many successive measurements before a meaningful determination of some average exposure parameter can be made.

Another problem is choosing locations to be measured or sampled so as to be representative of the radiological conditions. The survey should identify average and "worst-case" conditions in each location surveyed. If there is good reason to believe that measurements and sample collection vary fairly continuously and moderately over the area surveyed, a reasonable approximation is obtained by choosing a "network" of points as uniformly spaced as practical.

For radiological surveys of land, gamma radiation dose rates at some standard height (1 meter) are a measure of the average value over approximately 100 m^2.* This suggests a survey block approximately 10 meters on a side for intensive coverage of the land area. Instrument readings should also be observed in transit from one grid point to the next grid point to locate highly elevated concentrations.

The second-level survey, and possibly the most important part of a decommissioning survey program or any special monitoring program, establishes a complete record of the character of the land or structure prior to transfer to the alternative use. This phase of the study may include dose assessments for different types of human use as well as possible estimates of population health effects. This record should be developed and preserved indefinitely as was done, for example, for a former location contaminated with uranium and plutonium in Los Alamos, New Mexico.[15]

Because special surveys are performed for short periods and not indefinitely, as in the case of monitoring near operating facilities, periodic "check" surveys may be desirable for allaying local concern to determine the possible importance of any trends in radiation levels or radionuclide concentrations. These check surveys are beneficial whether or not decontamination or decommissioning is involved.

Limitations of Surveillance Programs

General

In order to meet the basic objectives of a surveillance program, considerable care must be taken to ensure that the program design is technically sound. The previous sections have outlined general monitoring philosophies and several types of surveillance programs designed to emphasize sampling "important pathways". For nuclear facilities, a monitoring program is normally formulated and implemented prior to the initial operation of the plant. In this case, the pathways should be selected based on the evaluation of the source terms, release mechanisms as well as environmental parameters, and land and water usage in the immediate vicinity of the operation. In the case of national surveillance programs covering larger geographic areas and uncontrolled global or geological releases of radioactive material, the basic pathway analysis concept is still applicable, but the scope of the program may be limited to high population density areas or regional areas of concern.

In most cases, the information gathered from an environmental surveillance program can not be used to determine the radiation risk to a population (or individual) exposed to all naturally occurring and man-made radioactivity inherent in or discharged to the environment. Current regulatory requirements limit the amount of radioactive material discharged offsite to a level at which, under normal dilution or diffusion processes in the environment, typical radiation detection equipment and laboratory radiochemical techniques do not have the sensitivity to determine the specific radiation flux or concentration for all radionuclides. However, this does not mean that the current monitoring techniques are antiquated or insufficient. The sensitivity of surveillance methodologies is sufficient to provide an upper bound on the radiation flux and radionuclide concentrations which, when coupled with the important pathway parameters, can lead to an upper limit estimation of the population dose and possibly the radiation risk.

Since, in many cases, the estimation of the radiation risk depends solely on the evaluation of the final results of the monitoring program, all aspects of a monitoring program should be treated with equal importance. Experience has shown that reliable results and interpretations can come only from programs formulated and implemented by individuals who are knowledgeable in all facets of the program. The areas to be considered are chemical and physical characteristics of the source terms, pathway selection, media to be evaluated, field sampling procedures, laboratory analytical techniques, radiation detection requirements, statistical interpretation of data, and dosimetric evaluation. If possible, the implementation of all program aspects should be under the direction of one organization rather than fragmented into areas of separate group responsibilities so that continuity and overall program understanding are maintained.

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*This is the height to which airborne surveys are often normalized and, though the area "sampled" is much larger than 100 m^2, airborne and ground-level measurements can and should be complementary.

In the past, the usability of the environmental data compiled from surveillance programs that did not stress equal importance of the individual monitoring components has been questionable. Current state-of-the-art radiation detection equipment and radiochemical techniques have the necessary sensitivity to measure radiation and radioactivity levels of about a millirem per year. Therefore, if the sampling protocol, i.e., station location, media sampled, and sampling techniques, is poorly defined or inappropriate, the resultant analytical measurements, no matter how precise or accurate, are meaningless and could not be used to estimate realistic radiological risks. Furthermore, it would be just as meaningless to have excellent sampling and laboratory analytical techniques if the chemical form of the nuclide in the effluent and mixing zone media has not been determined. In most cases, the chemical form of the radioactive material dictates the exposure pathways of importance. For example, many nuclides may be very soluble in process solutions but when discharged to a fresh or estuarine water environment form insoluble compounds that are unavailable for direct water pathway considerations. Similarly, volatile airborne contaminants may be in several chemical forms, some of which may not be collected by normal sampling means, e.g., radioactive I_2 and CH_3I.

In order to ensure the usability of the data compiled as part of the surveillance function, it is essential that a quality assurance (QA) program be an integral part of the program. The QA program should be applied to every major portion of the surveillance program, i.e., sampling and analytical techniques, recordkeeping, and dosimetric evaluation. The subject of quality assurance is discussed in Chapter 5.

To accomplish the stated objectives, the design and execution of the field sampling phase of a monitoring program should be given at least as much attention as laboratory analyses. Samples must be representative of the pathway under investigation in terms of time, space, and media characteristics of that pathway.

Environmental samples should be analyzed to determine those radionuclides released from a nuclear facility to the environment that have the greatest significance from the standpoint of radiation dose. This is necessary since radiation dose estimates can be made only on the basis of specific radionuclide measurements.

The ultimate use of environmental data will define the sampling program parameters. If primary interest is in average population dose assessment, compositing techniques will suffice. However, if there is a need for more detailed information such as defining a temporal distribution, analyses of individual samples will be required.

Because of their inherent lack of specificity and other limitations, measurements of gross radioactivity (gross alpha, gross beta, gross beta-gamma) generally are inadequate and therefore unacceptable for making estimates of radiation dose. In certain cases, measurements of gross radioactivity may be acceptable for screening purposes, e.g., when the radionuclide composition of the environmental media is not expected to change rapidly with time and when the results can be correlated with determinations of specific radionuclides from a selected number of similar samples. For example, air and water are environmental media for which comparative measurements of gross radioactivity may be acceptable.

Analyses of composite samples are often used to keep the analytical workload within reason without sacrificing significant information. Time composites for analyzing long-lived nuclides may be in order if short-term time variations are not important. Analyses of spatial composites may also be carried out depending on the objectives of a particular monitoring program.

Ambient Monitoring

ERAMS attempts to meet its objectives primarily through the location of one monitoring station per State for each sampling program. Only a few States with the highest population densities have more than one station. Therefore, ERAMS is able to effectively monitor only widespread contamination involving several States. The matter of locating at least one sampling station in each State is to assure the public that monitoring is being done in their State. ERAMS would probably not be effective for monitoring local contamination from an individual nuclear facility.

Because of the wide scope of a national program, the types of media analyzed are kept to a minimum. However, media such as airborne particulates and dietary samples should provide at least an indication of the magnitude of any trend of radioactivity in other pathway media. The distribution and levels of airborne and dietary radioactivity should be fairly uniform in a region with temporal variation on a seasonal basis.

For regional monitoring programs, the sampling frequency will depend on whether the source term is manmade or naturally occurring. In general, natural radioactivity in potable surface and ground water as well as surface air does not vary significantly in concentration over time unless changes occur in the watershed or geological formations. Therefore, the sampling schedule for pathway analysis of natural radioactivity can be made on a relatively infrequent basis.

While trend assessments may be done annually as for the ERAMS program, such is not the case for the assessment of doses. There are a number of technical limitations on dose assessment on the basis of regional data. Average exposure conditions for individuals in various places in the United States are variable as are the data from regional measurements to characterize such exposure conditions.

Nuclear Facility Monitoring

In recent years, there has been a trend to use environmental surveillance as confirmatory programs at nuclear facilities to verify the inplant controls on the release of radioactive materials or to verify that the releases of radioactive material to the offsite environment have met certain regulatory criteria for acceptable individual doses. Current regulatory guidance for environmental monitoring programs at commercial nuclear power plants has recommended evaluating only those direct pathways, or the last trophic level of a dietary pathway, that contribute to an individual's radiation dose. For example, only water and edible fin/shell fish would be considered important in the water pathway. For the confirmatory analysis of the liquid pathway, the lower and intermediate trophic levels (plankton, algae, consumer fish, and sediment) are not deemed relevant and do not enter into modeling techniques to evaluate individual doses. Of course, the correlation between the estimated dose values (probable upper limits) of the confirmatory environmental surveillance program and the predicted individual dose from the effluent monitoring program depends on the dosimetric parameters used in each program as well as the technical adequacy of the two monitoring programs. It should be pointed out that most dosimetric parameters for effluent monitoring are generic rather than site specific and were obtained from previous detailed scientific investigations of all components of a given pathway. Futhermore, the dosimetric parameters are normally very conservative and overestimate the resultant predicted radiation dose. Therefore, it would not be unusual to find that the absolute results of the programs are not in agreement.

A limitation to this approach is that direct measurement of radiation exposure, with its associated contribution to public reassurance, is missing. A few continuously monitoring and recording instruments located at a few key locations near some nuclear facilities (power reactors) would supplement more extensive passive gamma-ray monitoring. This would make it possible to provide information, if available, on a more timely basis for public reassurance.

No environmental monitoring program can be effective without direct knowledge of the effluent constituents as well as knowledge of the frequency of routine and nonroutine effluent discharges. Environmental samples should be analyzed to determine those radionuclides that are released from a nuclear facility to the environment that have the greatest significance from the standpoint of radiation dose. Determinations of specific radionuclide concentrations are needed in order to relate the results of the analysis to an estimated radiation dose level. As was indicated in the discussion of general limitations, because of their inherent lack of specificity and tendency for large variation, measurements of gross radioactivity (gross alpha, gross beta, gross beta-gamma) generally are inadequate.

The design and execution of the field sampling phase of a monitoring program should be given attention equal to that given the laboratory analysis. Very accurate and precise analyses of nonrepresentative field samples yield results that may appear to be valid but that are incapable of interpretation and not worthy of detailed analysis. The main goal of a sampling program is to obtain a sample that is representative of the medium under investigation in terms of time, space, and medium characteristics. For example, it would be inappropriate to rely on monthly grab samples of water if the plant discharges infrequently (16 hours per week) or if the effluent constituents vary dramatically over time.

Special Studies for Decontamination and/or Decommissioning

The first problem of this type of monitoring concerns the lack of acceptable environmental residual activity guidance, particularly for property that was contaminated with either natural or manmade radioactivity and, after some type of decommissioning, was transferred to a public use or one not involving radioactive material.

The second problem involves inadequacies in methods for the characterization of some radioactive contamination in the environment. Computational methods for dose assessment, including the estimation of effects on humans who may inhabit the property, have not been satisfactory, nor have measurement methods, including sampling methods, been entirely adequate. The latter problem seems partly attributable to the failure to employ some existing monitoring methods because of cost considerations and to ensure that adequate criteria and standards are available. Adequate criteria and standards are needed to improve cost estimation for any decontamination and decommissioning efforts and to improve the development of standard measurement methods. This oversight may have contributed to the concern of local citizens because surveys have been made repeatedly to ensure that the environmental characterization was complete or at least technically defensible. A corollary problem has arisen because of the lack of programs for systematic development of needed environmental instrumentation.

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DEFINITION OF CRITICAL PATHWAYS AND RADIONUCLIDES FOR POPULATION RADIATION EXPOSURE AT NUCLEAR POWER STATIONS

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The U.S. Nuclear Regulatory Commission's Regulatory Guide 1.109 identifies potential critical radionuclides and pathways of exposure at nuclear power stations and presents generic environmental transfer factors and calculational models for preoperational, and later operational, estimates of doses to individuals and population groups. The Guide also encourages use of site-specific factors where they are available. For consideration as a critical pathway, the sub-committee on Defining Critical Pathways considers the calculational approach of the Guide satisfactory so long as site-specific factors are used where available and all pathways are included that contribute at least 10 percent of the total site dose limits (specified in 10 CFR 50 Appendix I) or 1 mrem/yr (4 percent of the 40 CFR 190 whole-body limit), whichever is less. Critical pathways determined by preoperational estimates of radionuclide releases should be confirmed with respect to the source term when actual release data are available. Environmental monitoring of these pathways is necessary, but the effort may be reduced if environmental measurements show that the actual dose equivalent rates are below 1 mrem/yr.

(Critical pathways; environmental monitoring; radiation exposure)

Introduction

The International Commission on Radiological Protection (ICRP) has recommended that environmental radiological monitoring be undertaken by considering the critical radionuclides, pathways, and exposed population groups.[1] In this context, "critical" means "much more important than others"; the detailed definition is given in the Appendix. The U.S. Nuclear Regulatory Commission has followed this concept in its Regulatory Guide 1.109, which identifies potential critical radionuclides and pathways at nuclear power stations and presents generic environmental transfer factors and calculational models for preoperational estimates of doses to individuals and population groups.[2] The Guide also encourages use of site-specific factors and indicates the need to consider other pathways if the additional dose exceeds one-tenth of the total doses considered in the Guide. These pathways were selected with reference to the design objectives in 10 CFR 50, Appendix I, which range for various pathways from 3 mrem/yr to 20 mrad/yr per reactor unit. The question considered here is whether the pathways and radionuclides selection in Regulatory Guide 1.109, together with the additional recommendations in it, are sufficient guidance for selecting critical pathways and radionuclides at nuclear power stations, or whether more specific criteria can be recommended.

Prudence requires that radionuclides and pathways be considered that result in doses well below the design objectives so that no critical ones are overlooked. As indicated in Chapter 3, the numerical values of the generic factors have the relatively large uncertainties that are usually encountered in values derived from environmental observations, and these uncertainties are compounded in complex pathways.[3] Hence, unless a significantly large margin of safety is incorporated, application of these generic factors to a specific site may erroneously eliminate from the critical category some radionuclides or pathways. Inclusion of unimportant radionuclides and pathways should be avoided as much as possible, however, because it trivializes the program and dissipates the limited resources available for monitoring, except that one may wish to monitor certain non-critical pathways for reasons other than dose assessment, as discussed in Chapter 1.

Selection of Pathways and Environmental Monitoring Activities

Critical pathways and radionuclides are defined here as those that deserve primary consideration on the basis of the recommended calculational approach as being mechanisms of principal radiation exposure to individuals. For considerations of inclusiveness, the calculational approach in Regulatory Guide 1.109 is satisfactory so long as site-specific relationships are used where available and all pathways are included that contribute at least 10 percent of the total 10 CFR 50, Appendix I, dose limits for the site or 1 mrem per year (4 percent of 40 CFR 190 limits), whichever is less. To assure that no important pathway is overlooked, it is desirable to prepare a check-list of pathways and radionuclides to subject all to preliminary calculational analysis. Lists of generally applicable pathways have been prepared,[4] but each site must be evaluated for its own characteristic pathways. The identified critical pathways and radionuclides would be expected to be monitored in the environment.

Pathways and radionuclides that produce significant collective (population) dose commitments should be considered equally with those that cause individual doses. It is possible, however, that consideration of such pathways will indicate that they are not suitable for environmental monitoring because of expected undetectable levels of activity.

The operator of a nuclear power station should have the option of eliminating unnecessary monitoring activities by demonstrating that the calculational model unduly overestimates the dose. Improved transfer factors can be applied by analysis of data from at least two years of routine monitoring, or by brief studies under the range of pertinent conditions. Because such reduced environmental monitoring places the main burden of the radiation protection program on effluent monitoring, the measured radionuclide source terms must be demonstrably accurate, as confirmed by independent quality assurance programs.

Additional Studies

In order to place these recommendations on a firmer factual basis, it is recommended that the factors used in the calculational model for the critical pathway be periodically scrutinized for reliability[4] and evaluated through additional studies where necessary. Useful information may also be available from facility monitoring programs and special studies, if only to indicate upper limits of transfer factors.

It is anticipated that the Nuclear Regulatory Commission will develop similar Regulatory Guides for other nuclear facilities to calculate doses to individuals and population groups, and that these Guides will identify the common critical pathways and radionuclides. Until these become available, such other facilities will have to be examined in detail with regard to radioactivity source terms, pathways, and points of population radiation exposure to assure that no critical pathways are omitted.

Appendix: Definition of the term "critical"[1]

Critical. "The word 'critical' has been used by the ICRP to describe the organ of the body whose damage by radiation results in the greatest injury to the individual (or his descendants). The injury may result from inherent radiosensitivity or indispensability of the organ, or from high dose, or from a combination of all three. The use of the term "critical" has here been extended to describe nuclides, articles of diet, and pathways of exposure which deserve primary consideration as being the mechanisms of principal exposure of individuals. By a further extension, the term has been used to describe groups of the population whose exposure is homogeneous and typical of that of the most exposed population."

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PROPAGATION OF UNCERTAINTIES IN ENVIRONMENTAL PATHWAY DOSE MODELS

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The uncertainty in the dose predicted by environmental pathway and internal dosimetry models can be estimated from an analysis of the statistical properties of the input parameters. This chapter presents one method, known as "imprecision analysis," for propagating the uncertainties in the multiplicative chain model for calculating the dose to an infant's thyroid from iodine-131 via the pasture-cow-milk pathway. For this pathway, the largest source of uncertainty is the dose conversion factor, which contributes nearly half of the uncertainty. Some of the uncertainty due to other parameters can be reduced by obtaining site-specific data. Because critical assumptions were required for this approach, testing of the complete model by field measurements will be necessary to determine the true uncertainty.

(Dose assessment; imprecision analysis; pathway models; uncertainty propagation)

Introduction

Limits on the amount of radioactivity in effluents released to unrestricted areas established by the Nuclear Regulatory Commission for its licensees are given in 10CFR20. The values listed in Appendix B, "Concentrations in Air and Water Above Natural Background," can be easily measured by state-of-the-art techniques. Implementation of the "as low as reasonable achievable" criterion in 10CFR50, Appendix I and the regulations of the Environmental Protection Agency in 40CFR190, however, set limits on doses to individuals. Since some of these doses cannot be directly measured, it is necessary to rely on calculations based on the amount of radionuclides in the effluents released from licensed facilities.

Because the levels of radioactivity in the environment resulting from routine releases of radioactivity by nuclear facilities are expected to be too low to be accurately measured, dose assessment is based on environmental pathway models and internal dosimetry models. Predictions of dose to any single individual are subject to uncertainty as models are only characterizations of reality and their input parameters are inherently variable. For environmental pathway models the best method of determining the uncertainty associated with model predictions is experimental validation (i.e., the comparison of model predictions with field observations). Unfortunately, model validation experiments are usually not feasible because of their cost and the difficulty in detecting low concentrations of radionuclides.

An alternative approach relies on an analysis of the statistical properties of the input parameters in order to estimate the overall imprecision in the calculated dose to specific individuals. Such an imprecision analysis requires two critical assumptions: (1) the model is a correct representation of reality and (2) the available data for input parameters are representative of the true distribution of parameter values. This approach has been applied to the pasture-cow-milk pathway to calculate the dose to infants' thyroids.[1,2] This pathway was chosen as an example of propagation of uncertainty because of its importance in reactor licensing and because a range of data for input parameters are available from the literature.

The model used to calculate doses to an infant thyroid from ^{131}I via the pasture-cow-milk pathway is a simple multiplicative chain

$$R = \chi \cdot k \cdot V_D \cdot 1/\lambda_{eff} \cdot Q_F^T \cdot f_s \cdot f_p \cdot F_m \cdot U^M \cdot D,$$

where

χ = equilibrium air concentration (pCi/m^3);

k = a unit conversion factor (86400 sec/day);

$1/\lambda_{eff} = T_{eff}/ln2$ = effective mean-time on pasture vegetation (days);

Q_F^T = total daily dry matter intake of a dairy cow (kg/day);

f_s = fraction of the total dry matter intake composed of fresh forage;

f_p = fraction of a year that dairy cows receive fresh forage;

F_m = intake-to-milk transfer factor (day/liter);

U^M = annual milk consumption rate for infants, ages 0.5 to 1.5 years (liters/year);

D = thyroid dose conversion factor for infants, ages 0.5 to 1.5 years (mrem/pCi-ingested);

R = annual dose (mrem/year) to the thyroid;

V_D = an air concentration - pasture grass transfer factor (m^3/kg, dry wt. · sec).

Details of the analyses and similar sections for other pathways can be found in the report, "A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides".[1]

Statistical Evaluation

The statistical evaluation of predictive uncertainty is based on estimating the distribution of doses calculated by the air-grass-cow-milk-child pathway given the distributions of parameter values for that model. The parameter distributions are obtained by an analysis of data available in the literature. Since these data represent samples of convenience and judgement, they contain a bias which cannot be assessed. The dose distribution is biased both by the parameter data and by the limitations of the pathway model itself. Since the bias introduced by the parameter data and the model structure are unknown, the evaluation used here is referred to as an imprecision analysis. The relationship between the predicted and the true distribution of individual doses could only be determined by a model validation study. However, for the example given here the assumption made is that the structure of the model is correct and that the parameter data are independently distributed and unbiased.

The imprecision analysis for this pathway has been performed analytically. Numerical techniques (Monte Carlo) have also been developed for this purpose.[3] The analytical approach involves estimating the mean μ and variance σ^2 of the log-transformed data for each parameter in the model and assuming the parameters are independently distributed. In this case the sum of the means of each log-transformed parameter will then equal the mean of the logarithm for the distribution of the model output.

$$\mu(\ln R) = \mu(\ln \chi) + \ln k + \mu(\ln V_D) + \mu(\ln \lambda^{-1}\text{eff}) + \mu(\ln Q) + \mu(\ln f_s) + \mu(\ln f_p) + \mu(\ln F_m) + \mu(\ln U^M) + \mu(\ln D).$$

Similarly, the sum of the variances of each log-transformed parameter will equal the variance of the distribution estimated for the model output.

$$\sigma^2(\ln R) = \sigma^2(\ln \chi) + \sigma^2(\ln V_D) + \sigma^2(\ln \lambda^{-1}\text{eff}) + \sigma^2(\ln Q) + \sigma^2(\ln f_s) + \sigma^2(\ln f_p) + \sigma^2(\ln F_m) + \sigma^2(\ln U^M) + \sigma^2(\ln D).$$

In a multiplicative chain model of this sort, the multiplication of values is equivalent to the addition of logarithms of these values. Thus, if

$$\text{Dose} = A \cdot B \cdot C,$$

then

$$\text{Dose} = \exp(\ln A + \ln B + \ln C).$$

The addition of normally distributed variables yields a quantity that is also normally distributed. Furthermore, if the number of parameters in the model is sufficient and if the total variance is not dominated by the contribution of any individual parameter, the final distribution will, according to the Central Limit Theorem,* also approximate a normal distribution regardless of the type of distribution associated with each input parameter. A variable whose logarithm is normally distributed is itself lognormally distributed. Thus, the sum of the means and the sum of the variances of log-transformed parameter values can be assumed to be the mean and variance of the logarithms of a lognormal variate.[4] Since the distribution of the model output has been assumed to be lognormal, any quantile of that distribution is determined by the values of the distribution parameters, μ and σ^2. For example, the most probably value or mode (X_p) is

$$X_p = \exp(\mu - \sigma^2)$$

the geometric mean or median (X_m) is given by

$$X_m = \exp(\mu);$$

the arithmetic mean is

$$\bar{X} = \exp(\mu + \sigma^2/2);$$

the 84th percentile is

$$X_{84} = \exp(\mu + \sigma);$$

and the 99th percentile is

$$X_{99} = \exp(\mu + 2.33\,\sigma).$$

In lognormal statistics, reference is also made frequently to the geometric standard deviation S_g. The geometric standard deviation is the value, which when multiplied by and divided into the geometric mean, gives an interval of values within which 68 percent of the distribution is located. The geometric standard deviation is

$$S_g = \exp(\sigma).$$

Comments on the Data

Although the literature is rich in data on ^{131}I transported through the air-grass-cow-milk-child pathway, very few studies could be found in ORNL/NUREG/CR-1004 that could be related directly to the parameters as defined by the model. Most measurements have been conducted over only short time periods, whereas the model parameters are assumed to be averaged over reasonably long time periods (e.g., the length of the grazing season). To account for this shortcoming, judgement was exercised and only average values derived from each published document were used in the analysis whenever appropriately averaged data were unavailable.

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*See Rao (1965) p. 128 for a more formal statement and discussion of the Lindberg-Feller form of the central limit theorem.[5]

Results and Discussion

A summary of statistical information is presented in Table 1 for each model parameter. The result of the imprecision analysis using lognormal statistics to propagate the uncertainties in the multiplicative chain model is given in Table 2. The column in Table 1 headed "NRC" contains typical values used by the Nuclear Regulatory Commission in evaluating doses to individuals and are provided for a comparison with the data from the literature. More site specific data may be used as is deemed necessary. The results of the data from the literature presented in Table 2 give a geometric standard deviation of 2.9. The calculated 84th percentile is about three times the geometric mean value and the 99th percentile is about ten times the geometric mean value of the dose calculated from a concentration of $^{131}I_2$. It should be stressed that these are calculated percentiles and that the values for the true distribution may be different.

Because of the unknown bias in the data and model structure as well as the inherent imprecision in dose estimation, an absolute guarantee that no individual child will receive a dose in excess of a prescribed individual dose limit cannot be given. About one-half of the uncertainty is from the thyroid dose conversion factor for infants. The refinement of this input in the dose model is not practical due to the difficulty in measuring this parameter. Some of the other uncertainties may be reduced by obtaining site-specific information for the input parameter and considering the various chemical forms of ^{131}I actually released by a nuclear facility. The variability within these dose parameters as indicated by the global literature will remain unless additional data or more site-specific data are used in the model. The determination of an acceptable probability that calculated doses will not underestimate actual doses received by a given member of the population could ultimately be based on the health risk associated with a particular range of dose limits and the potential increase in risk related to that portion of the estimated dose distribution which may exceed the dose limit. For example, a dose calculation to determine compliance with a 500 millirem dose limit may require greater accuracy than that to comply with a 25 millirem dose limit.

A numerical approach using Monte Carlo techniques has been used to analyze uncertainties in environmental model predictions.[3] The results obtained with this approach, using an assemblage of normal and lognormal distributions for each parameter and truncating these distributions at observed maximum and minimum values, are not significantly different from the results given in Table 2. The distribution of dose determined in this manner is illustrated in Fig. 1.

Conclusion

The approaches used herein to propagate uncertainties in environmental dose models indicate that the variability in dose estimation may be quite large, even for a select group of the population. We recognize that quantification of the uncertainty associated with environmental pathway dose models is best accomplished by conducting field tests under the conditions for which the models were intended. However, such experiments are difficult and expensive to perform. In addition, measurement of some input parameters such as the internal dose conversion factor is impractical. Therefore analytical and numerical methods to investigate the inherent propagation of uncertainties resulting from parameter imprecision will offer the best alternative approaches in lieu of model validation. Improvement in these techniques will require an increase in both the quantity and quality of relevant data for environmental transfer parameters as well as quantification of statistical correlations between parameters. Identification and quantification of site-specific driving variables such as soil pH, temperature, agricultural practices, season and climate, which may influence the values of the parameters should also contribute to a reduction of imprecision and an increase in predictive accuracy.

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Table 1. Statistical properties of the parameters used to calculate the dose to a child's thyroid resulting from a given air concentration (χ) of $^{131}I_2$.

Parameter	Units	n	X_p	X_m	$\bar{X}$	X_{84}	X_{99}	Range of data	NRC
V_D	$m^3/kg\cdot sec$	2	0.12	0.12	0.12	0.13	0.14	0.115 to 0.123	.039
$1/\lambda_{eff}$	days	10	5.9	6.0	6.1	7.0	8.4	5.5 to 7.2	7.4
Q_F^T	kg/day	2927*	16	16	16	19	22	6 to 25	12.5
f_e	-	2927*	0.43	0.43	0.43	0.56	0.73	0.1 to 0.8	1.0
F_m	day/liter	20	7.4E-3	1.0E-2	1.2E-2	2.3E-2	4.0E-2	2.7E-3 to 3.5E-2	.006
f_p	-	11468*	0.40	0.40	0.40	0.62	0.91	0 to 1.0	1.0
U^M	liter/year	45	290	300	300	370	480	175 to 431	330
D^{**}	mrem/pCi	-	6.8E-3	1.1E-2	1.4E-2	2.2E-2	5.7E-2	-	.014

n - Number of averaged values used in the analysis

X_p - Mode or most probable value of estimated distribution.

X_m - Median or geometric mean of estimated distribution.

$\bar{X}$ - Arithmetic mean of estimated distribution.

X_{84} - 84th percentile of estimated distribution.

X_{99} - 99th percentile of estimated distribution.

Ref: Hoffman and Baes (1979).

* Herd averages; distribution appears to be normal.

** Estimated using statistical properties of thyroid mass, thyroid uptake, and retention for children ages 0.5 to 2 years.

Table 2. Propagation of uncertainties in the air-grass-cow-milk-child pathway model for $^{131}I_2$.

Parameter	μ^*	σ^{2**}	Contribution to the total variance (%)
V_D	-2.1	0.002	0.18
$1/\lambda_{eff}$	1.8	0.02	1.8
Q_F^T	2.7	0.014	1.3
f_s	-0.87	0.058	5.2
F_m	-4.6	0.3	27
f_p	-1.0	0.17	16
U^M	5.7	0.04	3.7
D	-4.5	0.49	45
R/χ***	8.5****	1.1	100
R/χ (mrem · m^3/pCi · yr)		X_p = 1600	X_{84} = 14000
		X_m = 4900	X_{99} = 51000
		$\bar{X}$ = 8500	

*Mean of log-transformed data.

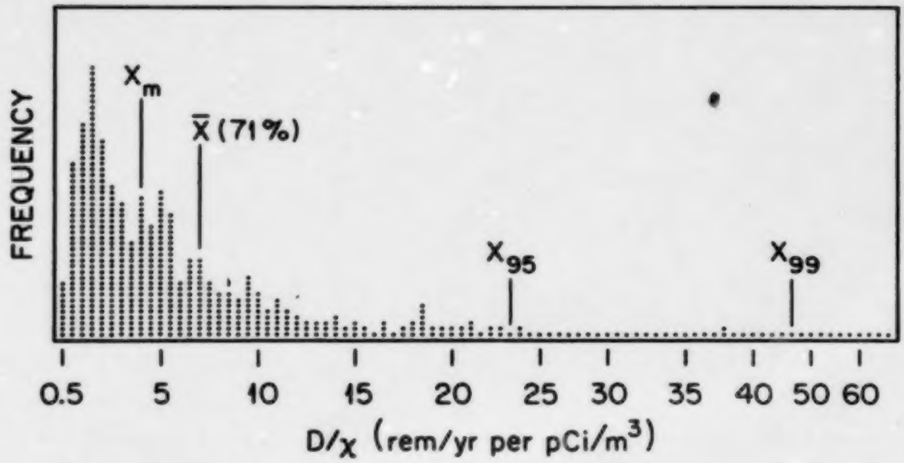
Ref: Hoffman and Baes (1979).

**Variance of log-transformed data.

***Annual thyroid dose resulting from 1 pCi per m^3 of $^{131}I_2$ in air.

****Calculated by adding (ln 86400 sec/day) to $\Sigma\mu(-2.9)$.

DOSE TO AIR CONCENTRATION RATIO (D/χ) FOR INFANTS FROM INGESTION OF ^{131}I VIA THE PASTURE-COW-MILK-PATHWAY



DETECTION OF CHANGES IN ENVIRONMENTAL LEVELS DUE TO NUCLEAR POWER PLANTS

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This committee report reviews the sources for sudden and slow variations in detectable radiation levels in environmental samples from nuclear power plants. The statistical nature of the operational and preoperational data makes it important to determine their accuracy before evaluation of any apparent deviations. Recommendations are presented for improved identification of transient events and for procedural developments.

(Background radiation; counting statistics; environmental monitoring; fallout; low-level detection; power plant effluents)

Nature of the Problem

Nuclear power plants are required to monitor liquid and gaseous effluents and radioactive contamination in air, water, soil, vegetation, food stuffs (milk) and selected animals. Accidental releases of radionuclides should show up in the effluent monitors and, depending on the pathways involved, may appear in environmental samples.

Since the levels of radioactivity involved are very low, small fluctuations in background, for whatever reason, may mask any increase in levels due to releases from the power plant. Such fluctuations may be internal in nature, e.g. due to counting statistics, sampling procedures, radiochemical procedures or fluctuations in meteorological conditions, or external, due to variations in cosmic ray background, weapons test fallout or to emissions from other power plants, whether nuclear or coalfired, or users of radionuclides in the same general area.

Unexplained fluctuations in readings on environmental samples have occurred on many occasions. The problem is how to reduce such occurrences or, alternatively, how to identify more effectively the cause of these fluctuations. In particular, it is important to determine if operational survey results should be compared with preoperational data or with contemporary data obtained at control locations well off site. Many of the fluctuations observed require careful statistical analysis for proper evaluation, but the depth of such evaluations may be limited by cost and manpower considerations.

Regulatory Background

The magnitude of the radiological impact has been described in the "GESMO Report" (NUREG-0002), ORNL-5315 and EPA 520/1-77-009. In many cases these make conservative assumptions, in effect overestimating levels, so that measured concentrations may be expected to lie well below them. Environmental monitoring programs for nuclear power plants are typically entrenched in the requirements for the operating license (Tech Specs) to assure compliance with Appendix I of 10CFR50 and NRC Reg. Guide 1.21. There is a great deal of variation in monitoring programs from plant to plant and attempts are being made to introduce greater flexibility, without the rather cumbersome amendment process. Reg. Guides 4.1 and 4.8 outline recommended surveillance programs and (ideal) detection sensitivities and Reg. Guide 4.15 describes the program design for quality assurance of such programs. Being generic and rather general in nature those guidelines do not address themselves fully to the problems posed to this Committee, namely how to distinguish between internal and external variations in environmental samples and how to identify a specific source of origin. Furthermore, at most plants collection and reporting of radiation data is mandated by Tech. Specs., but their analysis is not.

Specific Causes of Variations

Transient Release of Liquid or Airborne Radionuclides by the Nuclear Power Plants

Transient release to air or water may be due to failure of plant equipment, human error, planned waste discharges or certain accidents affecting plant systems integrity. One consequence may be the undetected appearance of short-lived nuclides.

The detection and evaluation of the consequences of such events is the principal reason for operating environmental surveillance programs. The release may be sudden and brief or may lead to continued, slowly changing concentration levels. In general, many such events should be immediately evident on the effluent monitors and trigger implementation of both precautionary measures and, if the release is large enough, immediate intensification of the environmental sampling program. However, this may not be the case for samples that are monitored only periodically, such as iodine-131 in air, particulates in off-gases, or tritium in air or water.

A problem arises if the release is fairly small and so transient that it escapes detection by the effluent monitoring system due to the time constants employed. This is one case where it is essential that the environmental surveillance system must respond adequately, allowing for natural dispersion times and processes. Occasionally, at some nuclear facilities, a short, intense release of activity may overwhelm the effluent monitors, making a quantitative assessment difficult. Another common situation arises when not all release points are monitored, so that some pathways or effluents are not accounted for properly.

Fallout from Atmospheric Nuclear Weapons Tests

The Chinese and, earlier, the French atmospheric weapons tests led to measurable increases in environmental levels even on the fourth or fifth passage around the globe. Residual effects in crops and water were observed for weeks after and some long-lived tracers from much earlier tests still linger in soil and vegetation. Timely notification helps in identifying causes of observed increases and in planning for the collection of additional samples. Principal effects arise from iodine-131 in milk, strontium-89 in vegetation, and some shorter-lived fission products in air filters and marine organisms. TLD dosimeters may be affected and their evaluation also would need timely information on fallout levels in surrounding areas.

Effects of Effluents from Coal-Fired Stations

There is increasing awareness of the presence of uranium and thorium and their daughter radionuclides in fly ash and in the airborne particulates emitted by coal-fired stations. In certain localities, under particular meteorological conditions, this excess activity may significantly increase the radioactivity levels (gross beta or gamma) monitored near nuclear power plants. After some time, plant operators may learn to allow for this, and in practice additional measurements may have to be incorporated in the surveillance programs, to permit identification.

Technologically Enhanced Airborne Concentrations from Industrial and Medical Activities

In certain areas increases in ambient radioactivity levels may arise from mining activities involving minerals, such as shale, phosphates, or granites, that may lead to a significant increase in radon and radon daughter levels in the air.

In construction, earthmoving operations may cause significant increases in airborne radioactivity detected in filter samples, mainly due to radon daughters. High dust levels may increase airborne concentrations of Be-7 by resuspension. Air monitoring stations in heavily trafficked areas may be particularly susceptible. Similar increases may arise from the use of phosphate fertilizers in dry form. Effluents from hospitals, radiopharmaceutical plants, research laboratories, and other radionuclide users may introduce substantial and erratic levels of frequently short-lived radioactivity into the environment.

Variations in Natural Background Radiation Levels

As detectors of increasingly greater sensitivity are employed, variations in natural radiation background form the largest contribution to the measurement uncertainty and hence, affect the ability to recognize the reality of a small but statistically significant increase in environmental activity observed. Short-term variations in cosmic ray intensity may arise during solar flares and other geophysical disturbances affecting the upper atmosphere and may be particularly noticeable at higher altitudes. Radon levels in the atmosphere will vary with meteorological conditions, precipitation, and snow cover. Preoperational surveys should establish "typical" seasonal fluctuations in atmospheric radon levels and the magnitude of daily fluctuations, both for air samples and in well water. However, additional short-term variations may arise from a multiplicity of causes.

Variations Due to Improper Radiochemical Procedures and Calibrations

In several instances sudden increases in activity in environmental samples have been reported that, on investigation, were found to arise from sudden and ill-documented changes in radiochemical extraction procedures or changes in standards. While these changes presumably resulted in more accurate results, the apparent changes in reported activity were often left unexplained and hence, in the absence of any explanation, had to be assumed to be due to plant operations. Such occurrences can be minimized by a critical review of reported data and improved quality control programs. Another possible source of occurrences is unsuspected contamination of facilities, samplers, or reference samples.

Instrumental Fluctuations

A major contribution to variations in recorded data results from systematic fluctuations in detector response. In the case of TLD's this may be related to variable dark current, changes in thermoluminescence, and reader performance. There are also variations in the detector "constant," the inherent difference in response rate of individual dosimeters. With other detectors it may depend on variations in humidity, temperature, supply voltage or the movement of calibration sources, without the technician doing the work being aware of these effects. These effects can be minimized by frequent recalibrations and background counts but in many cases the demands on equipment and staff time impose practical limitations on their frequency. Ten to twenty-five percent of operating time has been suggested as being appropriate for this purpose. A further means of ensuring more consistent detector operation is through better understanding of detector parameters by the user.

Sampling Variations

Variations in output data are frequently encountered due to nonrepresentativeness of the samples, inconsistencies in the method of sampling from different sources, effects of weather and seasonal conditions on the nature of the sample and incompleteness of the monitoring plan, such as may occur if not all effluent pathways are monitored and recorded. Care must be taken to avoid cross contamination and to employ consistent procedures for sample collection.

Limits in Detection Sensitivity

Some determinations, particularly for iodine in milk, are at the limit of practical detector sensitivity for routine monitoring programs and should be recognized as being potentially unreliable. As a result, excessively large counting times may be required for adequate statistical precision; failing this, rather large variations may be expected in the results for comparable samples. Instrument stability also imposes practical limits on counting time, so do diurnal variations in background. There is then a tradeoff between the number of comparable samples that can be analyzed and the consistency of results. Thus some uncertainty may exist as to whether a transient increase in observed activity was real and deserves further investigation.

Recommended Technical Solutions

The above sources of variations are clearly not of equal importance and some of them may be soluble by changes in equipment or technical procedures, while others call for additions or modifications in administrative or regulatory procedures. However, the basic problem is technical in nature and changes in regulatory procedures can merely change the degree in emphasis. Much information related to this can be found in NCRP Report 45. Any proposed solutions must address themselves to two different aspects:

One concerns the positive identification of any observed change in measured environmental radioactivity as being statistically significant, i.e. "real" in that sense. This should then be followed, by assigning it to a specific cause if possible. Since most of the effects to be observed are expected to be small in amplitude, any statistical evaluation depends on the standard comparison value chosen, which may be based on preoperational surveys, or simultaneous monitoring results elsewhere in the region.

The other aspect is procedural in nature, by attempting to improve detectability of small events by improved methods of sampling, of analysis, or by organizational measures. Clearly no one approach will adequately cover the various situations described in the preceding section.

Identification of Transients

It is generally agreed that the concept of a detectable "increase" in measured ambient activity is meaningful only if one can answer the question: Increase over what? This implies that there is a statistically valid difference in measured level between that determined at the time and place of interest and some previously established "background" level. This background may have been determined either during the preoperational survey, preferably over a 2-3 year period, or it may represent the average of a number of readings obtained during operations off-site, upwind or upstream.

Ideally these background readings should be analyzed for daily and seasonal periodicities to permit extrapolation for future measurements. Optimum use of this information requires development of an accessible computer program capable of evaluating environmental measurements. The statistical nature of the data available must be examined carefully and their use in providing more reliable information should be analyzed. A sufficient data base must be established to permit prediction of background levels during operation. The control locations themselves must be validated to exclude any reference location with normally high background levels from any continuing cause.

Data Analysis

Mere collection of environmental data without careful scrutiny is certainly not in the spirit of the law. In many cases more detailed analysis of reported data than currently employed is highly desirable.

To identify causes of specific events comparison with a predictive model should be done to account for seasonal variations, precipitation effects of radon levels, fallout increases in spring, etc.

Development of a proper statistical data base then facilitates evaluation of measurements with their standard deviation in comparison with preoperational data and control locations.

Analysis of current data should also be used to establish the validity of the predictive model and to adjust its data base if appropriate.

Development of a Predictive Model

The above suggestions lead naturally to a proposal that the industry obtain a predictive model for their site that will produce data on background variations, probable effects of weapons fallout for specific samples, seasonal effects, sample locations and radionuclides. This undoubtedly will require some new development work as present predictive models are not sufficiently advanced.

Pathway analysis in most cases will indicate that only about 13 radionuclides participate in critical pathways, depending on location. Only four radionuclides or their isotopic ratios may be required for initial discrimination between fallout events and plant-related transients. Examples of these are cobalt 58/60, cesium 134/137, neptunium-239 and strontium 89/90.

Detector Response to Transients

It is recommended that plant operators examine their effluent monitors for their sensitivity to short-term transients. In some cases intensified monitoring may be required, especially for drinking water, to check unmonitored pathways, such as floor washings draining by surface runoff. For airborne pathways the pressurized ion chamber is the most satisfactory detector, but it is dominated by noble gases in effluents, so that other constituents cannot be distinguished. If the transient is due to defective operation of filters, frequent sampling of fenceline particulate detectors may be adequate.

Since periodic "grab" samples may miss short-lived transients, continuous monitoring leading to a composite weekly or monthly sample is preferred.

Procedural Recommendations

Some of the above suggestions require adjustments in the way surveillance programs are conducted and evaluated. Several of them involve cooperation between plant operators, contractors and local and federal agencies. Among these the following changes or additions in existing procedures are recommended.

Validation of Control Locations

Most surveillance plans use "control locations" to provide reference data with which plant-related effluent measurements can be compared. These locations typically are upstream for water samples and in locations ringing the plant in widening circles for airborne samples and well water. Occasionally such locations may be anomalous themselves, by being located on granite-bearing rock or on other sites with high radon levels, or from industrial sources. Unless such anomalies are recognized, these samples may skew the apparent average values used for baseline purposes. For this reason it is important to validate all control locations in the course of the pre-operational program.

This implies that comparison of monitoring data be conducted between indicator stations and control stations during the operational program. Consideration must be given as to whether the preoperational data set was sufficiently large in order to obtain mean and standard deviation values for validation of the control stations of the operational monitoring. Some emphasis should be placed on increased use of pressurized ionization chamber measurements in the selection of preoperational sampling locations and more attention to control station selection during the preoperational program. If the sampling period during preoperational monitoring is not representative, because of abnormal conditions, the period may require extension until representative samples can be obtained.

It is also clear that initial selection of control sites requires more care than has often been devoted to this matter and should be subject to subsequent validation.

Follow-up Procedures

Procedures should be developed to analyze environmental data when they are reported and to follow-up any apparently significant changes, to compare them with measurements at control stations, with any other plant or government site reporting data on a regular basis and with the preoperational levels.

The statistical validity of any deviation should be established and, as far as possible, any analytical errors or procedural mistakes should be noted to remove their consequences from the list of "significant" transients. What constitutes a "sufficient" data base has to be assessed in each specific case.

Any changes in sampling or analytical procedures should be identified that may result in a new range of standard deviations.

To avoid excessive additional costs the extra effort involved in these follow-up procedures should be evaluated for cost-effectiveness from time to time and new or continued sample collection should be justified.

Documentation

To maintain continuity and to assist in the follow-up described above it is important that records be kept of any procedural or instrumental changes that may affect results. This would include changes in TLD readers, changes in sampling procedures, analytical procedures or methods of sample compositing.

Information on Fallout from Other Transients

There is a clear need to improve the flow of information on weapons fallout and other releases from government agencies to the industry. Moves are underway for EPA to coordinate information flow from federal agencies to the states. However, we believe it would still be desirable to have a non-government group, perhaps under the auspices of the Health Physics Society or a National Laboratory, to ensure rapid dissemination of any such data to plant operators and environmental contractors.

Such a committee may also assist in publicizing and standardizing improvements in analytical techniques, cross calibrations of equipment and in developing sampling standards.

Data Presentation

To simplify the recognition of significant trends it is recommended that environmental measurements be presented, as much as possible, both in graphical form and in a computer-compatible format for continuing evaluation.

Uniformity of Evaluation

At present intercomparison between different plants and recognition of common events is difficult because of variations in the reporting format and in the evaluation procedure. It is recommended that the industry adopt uniform methods of data evaluation and report presentation; these could perhaps be developed through the coordinating committee (above).

Suggested Administrative Solutions

Flexibility in Tech Specs.

Present Tech Specs in many cases make it difficult for the operator to adopt critical pathway programs or to eliminate unneeded samples to concentrate on significant ones. In this connection Reg. Guides must recognize differences between ideal laboratory conditions and routine commercial operations. It is understood that some expected modifications in NRC Regulations may introduce greater flexibility.

Reporting on Environmental Radiation Levels

Central dissemination of environmental levels by a Government agency (perhaps EPA) would be most desirable, perhaps through a revival of the Radiation Data Reports. Some information of that type is distributed now, quarterly, by the USEPA Eastern Environmental Radiation Facility.

Emission from Industrial and Medical Radionuclide Sources

The significance of emissions from hospitals, manufacturers, coal-fired stations, etc. as well as sources of natural radioactivity should be evaluated to determine if the emissions from these facilities can significantly affect the levels of radioactivity in the environment of nuclear power plants. If it is determined there is significant potential for changes in measured levels, then the methods of analysis used for the nuclear power plants programs should be up-graded to make them more nuclide-specific. This then would allow for the differentiation between nuclides released from the nuclear power plant and those released from other nearby sources.

Coordination of Milk Sampling and Analysis

Some variations in reported data for milk may reflect dispersed responsibilities for sample collection and assaying. Some administrative action may be desirable to improve uniformity and coordination.

Certification of Analytical Laboratories

Periodic certification of analytical laboratories, including auditing of environmental monitoring records, by an appropriate agency may be desirable to assure quality and consistency of performance. This would be distinct from NRC inspections that focus mainly on compliance with regulations.

Short-Lived Radionuclides

The role of short-lived radionuclides not usually monitored or specified in surveillance programs should be examined as they may well account for unexpected peak counts, that cannot be verified later.

Quality Assurance Program

Procedures should be developed for comprehensive quality assurance programs in the management of releases and the operation of effluent monitors in accordance with Reg. Guide 4.15.

Training of Personnel and Upgrading of Detection Procedures

Personnel must be trained to recognize instrumental malfunction and attention to detail in detector performance. This may involve computer indexing of individual TLD characteristics, more frequent background checks and attention to low-level laboratory contamination and to source movement and storage. Upgrading of facilities at some plants would minimize errors.

Conclusions

Specific recommendations of this subcommittee are summarized as follows:

1. All environmental monitoring data (including preoperational data) should reside in an easily accessible computer data base.

2. Two or more years of preoperational data should be analyzed by sample type and location:

    a. To determine predictable periodicities (seasonal, diurnal, etc.)

    b. To identify any anomalies associated with specific sample types or locations

    c. To establish the validity of proposed control and indicator stations to be compared during plant operation

    d. To define expected statistical characteristics of the data

    e. To determine any interference from radionuclides released by other facilities

3. Operational environmental monitoring data from indicator stations should be compared with similar data from control stations. These analyses should include:

    a. Comparison of current individual indicator with control-data points using previously established standard deviations and cumulative averages from previous information to date (adjusted for predictable periodicity)

    b. Graphical presentation of current and previous information

4. Establish one or more groups:

   a. To develop uniform methods of data evaluation, presentation, and computer storage

   b. To provide central dissemination of environmental levels

   c. To develop procedures for the selection of control monitoring locations

   d. To ensure prompt notification of operators and analytical laboratories of regional or global events, such as weapons testing, that could affect environmental monitoring results

   e. To assist in improving and standardizing analytical techniques and sampling procedures

   f. To coordinate periodic cross calibrations among interested organizations

   g. To perform quality assurance audits of individual laboratories and their reported data and to provide periodic certification of these analytical laboratories

   h. To develop a generic statistical model to aid in prediction of changes in environmental radiation levels.

5. Establish comprehensive quality assurance programs in accordance with NRC Regulatory Guide 4.15.

QUALITY ASSURANCE FOR ENVIRONMENTAL MONITORING PROGRAMS

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Quality Assurance (QA) is the summation of all programmed events required to ensure that data being generated by a laboratory are as meaningful as possible. A comprehensive QA program must begin with management's commitment to quality results and continue through site selection, sampling, analysis, and data reduction until a final report is issued. This report is intended to be a guide for the development of a complete QA program. Detailed information relating to the many aspects of QA can be found in the references cited.

(Analysis; calibration; data reduction; data reporting; personnel; quality assurance; quality control; records; sampling; standards)

Introduction

Quality Assurance (QA) is the summation of all programmed events imposed internally and externally in order to ensure that data being generated by a laboratory are as meaningful as possible. Quality Control (QC) procedures, which are generally considered to be task specific, are a very important aspect of a comprehensive QA program but individually are not a guarantee of quality. A complete program must also take into account management's responsibility to provide an organizational structure and budget so that QC can be routinely implemented, administered and reviewed. Securing qualified personnel, providing training and supervision are as important as written QC procedures and record keeping. Before samples are collected or analyses performed, procedures must be developed, tested, and adopted to ensure not only the validity of final results but also the integrity of the original sample. Site selection, sample size, storage and preparation are just as important as the calibration of electronic counting equipment. The use of computers in the laboratory for process control, data reduction and report preparation has greatly relieved the burden of routine operations but has at the same time created new areas for QC. The goal of any QA program is to maintain the quality of results within established limits of acceptance. Quality assurance is not complete if it only detects substandard results while not providing procedures for remedial action.

It is the purpose of this document to provide a guide for the development of a comprehensive QA program. In most instances the reader will be directed to publications which provide adequate detailed information. Areas which are not adequately discussed in the literature will be covered here.[1-5]

Organization and Responsibilities

The first and most important aspect of a QA program is management's commitment to produce quality results. Once this premise has been accepted, a QA program can be established along the following steps published by K.R. Wilcox, Jr.[6]

1. Set objectives and policies to determine the quality of work needed.
2. Establish methods to evaluate the levels of accuracy and consistency achieved, and whether established standards are met.
3. Establish methods of initiating corrective measures if unacceptable accuracy is discovered.
4. Be certain that personnel are competent to perform the tasks required in the laboratory, including the quality control measures.
5. Institute the methods and evaluative tools with which personnel may determine whether or not they are performing properly. This includes training the personnel so they know the significance of the measures adopted and the application of the results to their own work.
6. Provide proper space, equipment, and materials for personnel to carry out the organization's missions.
7. Develop specific quality assurance objectives for the bench worker, and make it the worker's responsibility to meet these objectives. This step should be as much a part of one's work goals as keeping up with the workload. The worker should know what is expected of him.
8. Develop a monitoring system for periodic review so the supervisors and director know whether or not the system is performing as designed.

Finally, individuals responsible for QA must be given the authority to initiate, recommend or provide solutions and to verify the implementation of corrective actions when required. The amount of effort required to maintain a desired degree of quality depends upon: the types and importance of samples being analyzed at a particular time; the amount of method development or method evaluation being performed; and the laboratory's past history and demonstrated competence. Although no single percentage will be appropriate in all situations, 10% to 20% of a laboratory's total effort is generally considered to be adequate and necessary for QA.

Personnel Qualifications

Quality data can only be produced if the individuals performing the analyses are qualified. Education and past experience are not satisfactory indicators of proficiency. Every new assigned function should be preceded by an appropriate training program. Training should be performed by or under the direction of qualified supervisory personnel. Newly trained individuals should be certified as qualified upon the successful analysis of QC samples. Training and certification of personnel should be documented and recorded.

A number of government and academic institutions provide training for individual or groups in radiochemical methodology, counting and environmental monitoring.[7-9]

Operating Procedures

Written procedures that have been approved should become part of a permanent library subject to annual review. These written procedures should include all of the program's activities including sample site selection; sample collection; packaging, shipment, and receipt of samples for offsite analysis; preparation and analysis of samples; maintenance, storage, and use of radioactive reference standards; calibration methods, and instrument QC; and collection, reduction, evaluation, and reporting of data. In addition, procedures should be prepared which clearly outline the proper manner of record keeping.

Records

The records necessary to document all activities of a QA program should be specified. One key aspect of a QA program is maintaining the ability to follow a sample from selection to data reporting.

Records to accomplish this should cover the following processes: field sample collection and sample description; sample receipt and laboratory identification coding; sample preparation and radiochemical processing method; radioactivity measurements (counting) of samples, instrument backgrounds, analytical blanks; data reduction and verification. The individuals responsible for these various functions should be identified on these records.

Quality control records for laboratory counting systems should include the results of measurements of radioactive check sources, calibration sources, backgrounds, and blanks, as well as a complete record of all routine maintenance and service.

Records relating to overall laboratory performance should include the results of analysis of quality control samples such as analytical blanks, duplicates, interlaboratory cross-check samples and other quality control analyses; use of standard (radioactive) reference materials to prepare working standards; preparation and standardization of carrier solutions; and calibration of analytical balances. In addition permanent files should be maintained on personnel qualifications and results of audits including recommended remedial actions.

Sampling Procedures

Environmental radiation monitoring frequently requires the collection of water and air samples. Therefore, instruments used to measure the sample volume must also be incorporated into QC procedures so that accurate sample collection can be assured. Data pertaining to the calibration and performance of these instruments must be recorded and retained with the previously mentioned records. The importance of establishing and maintaining sample integrity cannot be overemphasized. If the sample is not representative of its environment the resulting data, regardless of the accuracy of the analytical measurement, will be meaningless. Written sampling and shipping procedures should specify containers and include any required sample treatment. Special attention should be given to liquid samples which might deposit some of their radioactivity on container walls. Sampling procedures[10-13] should indicate the number of, quantity of, and location where samples are to be obtained. Photographic and/or written documentation of the sampling should become an integral part of that sample's history.

Radioanalytical Procedures

Radioanalytical QC usually accounts for the largest portion of a total QA program. Undoubtedly, this is where the greatest QA effort should be because the sample is exposed to the greatest number of possible sources of error in the laboratory. Laboratory QC, therefore, must cover the following general areas of laboratory practice:

A. Analytical Methodology

B. Counting Instrumentation

C. Data Reduction

Analytical Methodology

Standard methodology used by all laboratories, for all radionuclides in all sample matrices might be ideal, but is unrealistic. However, even accepted standard methods of analysis must be subjected to rigorous testing of the worst probable sample matrix before being routinely implemented in a particular laboratory. Without proper control of reagent material and other areas of possible sample contamination by the use of blanks and blank data control charts, the best analytical methods will not yield the desired results. If extremely sensitive counting techniques are being used, contamination from ambient air supplies must be considered, e.g., carbon-14, radon daughters, thoron daughters, etc. Continuous laboratory monitoring can be accomplished by the introduction of known samples into the routine sample inventory. Blind replicates on samples known to be homogeneous can be used conveniently to check the reproducibility of both the procedure and analyst. Blanks can be used to check on contamination. The best way to demonstrate the overall accuracy of the procedure is by analysis of a standard reference material. A valid reference material contains a known quantity of the element being determined, is known to be homogeneous, and contains the most likely "real world" problems needing to be checked. Most emphatically, neither replication nor intercomparison with other laboratories, no matter how good the agreement, is conclusive proof of accuracy. Intercomparison with others is a valuable method of QC when the procedures employed are markedly different, employ direct measurements without involved sample pretreatment, or when the laboratory to which the comparison is being made is acknowledged to have expertise in the particular field being treated.

The following table lists a number of items that should be considered and adapted to meet a laboratory's analytical QC commitment.

TABLE I

ANALYTICAL METHODOLOGY QUALITY CONTROL

	Practice	Reference
1.	Separation of function and levels of activity	14
2.	Reagent quality	14
3.	Low level laboratory air supply	14
4.	Laboratory contamination	14
5.	Sample decontamination	13
6.	Reagent and sample blank control charts	13
7.	Standard reference materials	15-19
8.	Natural matrix materials	18-20
9.	Blind replicates	21
10.	Spiked samples and blanks	15,22
11.	Laboratory intercomparisons	23,24
12.	Calibration standards	25,32
13.	Purification and standardization of standards	17

Counting Instrumentation

In order to ensure that counting equipment remains in calibrations and functions properly, timely QC procedures must be followed. These procedures should begin with a complete and thorough documentation of a new system's characteristics. The system's responses to various input conditions should be recorded for future reference. In general, counting equipment operation should be checked daily and at regular intervals calibrated and monitored for background variations. Nonspectrometric counting procedures should include steps of sufficient specificity to verify sample purity, such as decay or absorber measurements.

The following table outlines a number of required features for a valid QC program.

TABLE II

COUNTING EQUIPMENT QUALITY CONTROL

Practice	Reference
1. Documentation of new instrument response characteristics	33
2. Daily stability checks and control charts	13,34
3. Periodic background and control chart	35
4. Periodic calibration and control chart	36
5. Primary calibration standards	37

Data Reduction and Reporting

Data reduction and reporting of final results require as much attention and control as any of the previous steps in the analytical procedure.[38,39] The value of any measurement is only as good as the uncertainty associated with it. Without some indication of the precision and accuracy with which the measurement was made, the user cannot make a valid interpretation of the results. In fact, with results near the detection limit, as is the case with many environmental measurements, the uncertainty is frequently more important than the result itself because it is the uncertainty that tells the user just how accurate the measurement was made. Consequently, every measured value must include an uncertainty due to all significant sources of inaccuracy involved. This does not refer to just the counting errors of sample and background as is frequently practiced, but must include every significant uncertainty incurred anywhere in the entire measurement process if it will affect the final result within the number of significant figures retained. Particularly, uncertainties in the activity of the radionuclide being determined, in the activity of the tracer recovered, in the activity of the tracer added, in counting times and efficiencies, in chemical yields, in backgrounds and reagent blanks, in sample volumes, etc. must all be evaluated and the significant ones propagated to the final result.[39,40] It must be emphasized that the statistical analysis of replicate determinations provides only an indication of the radom variability. A complete uncertainty assessment should also include the analysts' best estimate of any systematic biases. Reported values should include, in addition to the final result, a propagated total random uncertainty expressed as the standard deviation and an estimated overall uncertainty that combines all of the significant sources of inaccuracy.[39]

Terms such as "below detection limits", nil, none, trace, zero, negligible should not be used for reporting analytical results. Such terms indicate only that the substance was not in fact detected under whatever conditions used but give no quantitative information as to the level at which the substance was not detected. Reporting results as "less than" some minimum detectable activity results in some statistical loss of information and a slight bias in the results when large numbers of results are combined in obtaining averages. Undoubtedly, maximum information is retained when the results actually obtained, including negative values, are reported along with their associated statistical uncertainties.

It is equally bad practice to ever permit a measured value to appear to be more precise and/or accurate than it really is to prevent unwarranted and inaccurate conclusions from being drawn from the results. Statistical methods become quite inaccurate when applied to small numbers of observations such as generally encountered in environmental monitoring. Yet it is quite common to see standard deviations reported to three or more significant figures, or to have the last significant figure in the result and its associated uncertainty appear in different decimal places. The rounded standard deviation reported should not deviate from the original value by more than 20%. For example, if the computed standard deviation is 0.1635, it should be reported as 0.16 which differs from the original by only 2%. Rounding to 0.2 should be avoided because it differs from the original value by over 22%. The result itself is then rounded such that its last significant figure will be in the same decimal place as that of the uncertainty.

All too often data are reported without a final review by individuals who generated the data or without being proofread by the typers of the report. Hand calculations should be checked routinely by a second individual and periodically checked by resubmission of older data. The widespread use of electronic data processing has relieved one possible source of error while introducing a new one. Computer errors which are rare are usually catastrophic and can therefore be easily uncovered. True computer errors usually cause program failure or produce absolutely ridiculous results. However, subtle errors have been known to creep into a complex data reduction scheme. For this reason, resubmission of reference data should be included with all sample data submissions.

The following table lists the required features of a QC program in this area.

TABLE III

DATA REDUCTION QUALITY CONTROL

Practice	Reference
1. Error propagation	39-41
2. Calculation of lower limit of detection	10, 37, 39, 42, 43, 44-46
3. Data evaluation	43, 40, 47
4. Data reporting	38, 39, 48

Audits

A valid QA program is composed of numerous QC procedures and checks that often cross departmental lines of responsibility. Audits, therefore, should be made by individuals outside the department being audited. These audits should be frequent and allow the auditor to make recommendations for improvement and also follow-up on previous recommendations.

Quality assurance programs which are supported by management, administered by responsible individuals, implemented by committed and dedicated workers and audited by conscientious reviewers will insure the quality of environmental radiation data.

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REPORTING OF ENVIRONMENTAL RADIATION MEASUREMENTS DATA

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This report is intended to serve as a practical guide to treating and reporting environmental radiation measurements data. Recommendations for a uniform method of data reporting are presented and justified. Three primary requisites are considered: proper units, an appropriate number of significant figures, and an unambiguous statement of measurement uncertainty. Present practices are summarized and evaluated, and their deficiencies are examined. To avoid confusion, it is recommended that the existing multiplicity of units used to report various radiation quantities be reduced to a smaller consistent set. Use of the metric system of units is encouraged. Rules for rounding reported values to an appropiate number of significant figures are presented. The appropriate number of significant figures for a reported value is determined by the magnitude of the total uncertainty associated with the value. Guidelines are given for estimating random and systematic uncertainties, and for propagating and combining them to form an overall uncertainty. It is recommended that each reported measurement result include the value, the total random uncertainty expressed as the standard deviation, and the combined overall uncertainty. To avoid possible biases of data, all measurement results should be reported directly as obtained, including negative values. The lower limit of detection (LLD) should serve only as an *a priori* estimate of detection capability for the instrumentation, and not as an absolute level of activity that can or cannot be detected. The concept of a minimum detectable concentration (MDC) is introduced to serve as an *a priori* estimate of the capability for detecting an activity concentration with a given measurement instrument, procedure, and type of sample. Neither the LLD nor the MDC is intended to be an *a posteriori* criterion for the presence of activity.

(Accuracy; activity; data reporting; detection limit; environmental; error; lower limit of detetion [LLD]; measurements; minimum detectable concentration [MDC]; precision; radiation; random uncertainty; significant figures; statistics, systematic uncertainty; uncertainty; units)

Overview

This report highlights the guidelines and recommendations contained within a much lengthier version prepared by the subcommittee. The full report, *A Guide and Recommendations for Reporting of Environmental Radiation Measurements Data*, is available as a special publication of the National Bureau of Standards [1]. The guide and its recomendations are intended to be useful and specific. It is not intended to be a general or exhaustive theoretical treatment of measurement results, but rather to serve as a practical guide to treating and reporting environmental radiation measurements data.

There are three primal requisites to reporting measurement data. The reported value of a measurement result must always:

1) be unequivocal and properly dimensioned (i.e., the units must be clearly understood and suitable for the value);

2) be expressed in an appropriate number of significant figures; and

3) include an uncertainty statement (whose meaning is unambiguous).

Mistreatments of conditions (1) and (2) are usually not the most serious failings in data reporting. There is, however, considerable variation in the practices recommended and required by the various federal agencies concerned with environmental radiation data reporting. Recommended conventions to satisfy these conditions are covered in Parts I and II, respectively.

Failure to satisfy condition (3) is probably the most frequent abuse and is of greater concern. Unfortunately, almost all environmental radiation data presently being reported fall into one of three categories:

i) the value is reported without stating the uncertainty;

ii) the uncertainty is reported, but it is not specified:

iii) the reported uncertainty is specified, but is based on an incomplete assessment.

Further, federal practices pertaining to the reporting of uncertainties not only contribute to these abuses, but are also as diverse as the number of agencies and requirements specified within an agency's regulations. Recommendations for assessing, propagating and reporting uncertainties are given in Part III.

Perhaps the most non-uniform practices in environmental radiation data reporting are those involving detection limits. This and the teatment of results at or below these levels are covered in Part IV.

I. Dimensioning (Units)

As outlined in the Overview, the first requirement for the reporting of environmental radiation measurements data is that reported values must "be unequivocal and properly dimensioned." That is, the units for the values must be clearly understood and must be suitable for the value.

A survey and evaluation of typical units currently in use indicates that there are considerable variations in practice. This existing multiplicity is both needless and confusing. Two additional observations can be made. First, compound units (e.g., for radioactivity concentration) are frequently formed by using more than one prefix in forming the multiple of the compound unit (e.g., $\mu Ci \cdot mL^{-1}$). Accepted convention recommends that only one prefix be used [2,3]. Normally the prefix should be attached to a unit in the numerator. The second observation is that the conventional units of radiation quantities (curie, roentgen, rad, rem) are almost exclusively used and that few have converted to use of the International System of Units (SI).

It would be beneficial and helpful (to both laboratories and data users) if the number of units in use were reduced to a smaller consistent set. This goal toward greater uniformity could be accelerated by the encouragement of national use of the metric system, formally called SI, and by the use of standard metric practices and conventions. The familiar "curie," "roentgen" and "rem" are deeply entrenched within the radiological sciences and radiation fields, and will not be easy to forsake. This natural reluctance to change can be appreciated, but the eventual conversion to SI is inevitable and must be recognized.

In addition to our national commitment to the SI, there are many advantages to its use. Some of these are excellently described in the following brief summary from a British committee report[4]:

> The International System of Units (SI) is a rational and comprehensive system of units. It has seven base units. The unit for any physical quantity within the system is derived from one or more of these by multiplication or division and without introducing any numerical factors. The system is therefore coherent. It avoid the chaos of individual choice of units, it breaks down the barriers to communication arising from separate systems of units, and it removes the need for conversion factors that arises when incoherent units are used. The SI is clearly destined to become the universal currency of science and commerce. At first sight the use of the new SI units seems to bring little direct benefit to those...areas in which radiation quantities are extensively used, but their adoption is essential if these areas are not to be cut off from their parent sciences. The use of the new units for ionizing radiations will only extend the existing and growing application of SI....All changes bring their problems but the introduction of SI units does not change existing quantities although it does require people to become familiar with new numerical values.

A number of sources describing the use of the SI are available [2,3,5,6]. For environmental radiation measurements data, we are primarily concerned with the units for radioactivity, exposure, absorbed dose, and dose equivalent. The status of each of these, in terms of both the SI and non-SI units, will be considered in turn.

Radiation Units

Radioactivity is a measure of the rate of those spontaneous, energy-emitting, atomic transitions that involve changes in state of the nuclei of radioactive atoms.[14] It is given by the quotient of dN by dt where dN is the number of spontaneous radioactive events which occur in a quantity of a radioactive nuclide in the time interval dt[7]. The SI unit of activity is the becquerel (Bq), which is equal to one radioactive event per second, i.e.,

$$1 \text{ Bq} = 1 \text{ s}^{-1}.$$

The special unit of activity is the curie (Ci) which is defined as

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq} \quad \text{(exactly)}.$$

The International Committee for Weights and Measures (CIPM) has authorized, for a limited (unspecified) time, the use of the curie and its multiples. This temporary sanction was provided to allow time for familiarization with the new units.

Exposure, X, is the quotient of dq by dm where dq is the absolute value of the total charge of the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in a volume element of air

$$X = \frac{dq}{dm}$$

The SI unit for exposure is coulomb per kilogram ($C \cdot kg^{-1}$). The familiar unit for exposure is the roentgen (R) which is defined as

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C} \cdot \text{kg}^{-1} \quad \text{(exactly)}.$$

There is no special name for the SI unit of exposure ($C \cdot kg^{-1}$) as a replacement for the roentgen. As for the curie, temporary use of the roentgen has been sanctioned.

Absorbed dose, D, is the quotient of $d\bar{\varepsilon}$ by dm where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to the matter in a volume element and dm is the mass of the matter in that volume element [7]. The SI unit for absorbed dose and related quantities (specific energy imparted, kerma, and absorbed dose index)* is the gray (Gy). The gray, in SI base units, is a joule per kilogram.

$$1\ \mathrm{Gy} = 1\ \mathrm{J \cdot kg^{-1}}.$$

The gray is intended to replace the rad which is defined as

$$1\ \mathrm{rad} = 10^{-2}\ \mathrm{Gy}.$$

The unit rad has also been sanctioned for temporary use.

Dose equivalent accounts for the relative biological effectiveness of a given absorbed dose. It depends on the type of radiation, on the irradiation conditions, and, for a given organ, is inferred by weighting the absorbed dose in that organ by certain modifying factors[7]. The dose equivalent, H, is given as the product of D, Q and N, at the point of interest in tissue, where D is the absorbed dose, Q is the quality factor for the type or radiation, and N is the product of any other modifying factors.

$$H = DQN$$

The SI unit for dose equivalent is the sievert (Sv) which is equal to, in SI base units, $\mathrm{J \cdot kg^{-1}}$. Hence, when D is expressed in grays (Gy), H is in sieverts (Sv). The special non-SI unit for the dose equivalent is the rem. When D is expressed in rads, H is in rems. The unit rem has also been sanctioned for temporary use.

Compound Units

Compound units for other quantities are formed by combination of two or more units. The SI unit for *radioactivity concentration*, for example. could be $\mathrm{Bq.kg^{-1}}$ or $\mathrm{Bq.L^{-1}}$. *Exposure rate*, given by the quotient of dX by dt where dX is the increment of exposure in the time interval dt, is expressed in units of any quotient of $\mathrm{C \cdot kg^{-1}}$ by a suitable unit of time (e.g., $\mathrm{C \cdot kg^{-1} \cdot h^{-1}}$). The unit for *absorbed dose rate*, $\mathrm{dD \cdot dt^{-1}}$, is any quotient of the gray or its multiple or submultiple by a suitable unit of time ($\mathrm{Gy \cdot s^{-1}}$, $\mathrm{\mu Gy \cdot h^{-1}}$, $\mathrm{mGy \cdot yr^{-1}}$, etc.). As will be discussed shortly, there are a number of advantages to using an exponential notation instead of prefixes. The use of prefixes to form multiples and submultiples of the SI units is permissible, however, and for completeness is considered here.

Multiples and Submultiples of Units

Multiples and submultiples of the SI units are formed by adding prefixes to the names or symbols of the units. The SI prefixes are listed in Table 1. The unit of mass, kilogram (kg), is the only base or derived unit of SI that, for historical reasons, contains a prefix. The kilogram (not the gram) is the base unit, but multiples and submultiples of the unit of mass are formed by adding prefixes to the gram (g). Prefixes on the units are normally chosen and used to avoid excessive non-significant digits and leading zeros in numerical values. Two conventions in the use of prefixes should be mentioned.

1. Compound prefixes formed by combining two or more SI prefixes should never be used. For example, use GBq (gigabecquerel) not kMBq, or use µGy (microgray) not mmGy.

2. Only one prefix should be used in forming multiples or submultiples of a compound unit. Normally the prefix should be attached to the first unit listed in a product, or to the unit in the numerator of a quotient. For example, use $\mathrm{MBq \cdot L^{-1}}$ not $\mathrm{kBq \cdot mL^{-1}}$. The use of the unit kilogram is the only exception to this rule since the kilogram is the base unit of mass.

One should consult more comprehensive guides [2,3,6] for additional details.

TABLE 1
SI Prefixes

FACTOR	PREFIX	SYMBOL
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Special Units

There are a number of units which are not part of the SI, but are so widely used that they are accepted for continued use with the SI. The combination of these units with SI units should be restricted to special uses in order to not lose the advantage of the coherence of SI units. Those of interest for environmental radiation measurements data include the units of time: minute (min), hour (h) and day (d); and the special name liter. The recommended symbol for the liter is "L" in the U.S., not the lower case "l" which may be confused with the numeral

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*For definitions of these quantities see, for example, ICRU Report 19[7].

"l"[6]. The SI unit of volume is the cubic meter (m^3), and it or one of its multiples or submultiples is preferred for all applications. In any case, the special name liter is restricted for use with only liquid or gas volumes. No prefix other than milli should be used with liter.

As noted earlier, the common non-SI units for radiation quantities (curie, roentgen, rad and rem) are authorized, for a limited time, for use with the SI. These are destined to be replaced by the becquerel (Bq), coulomb per kilogram ($C \cdot kg^{-1}$), gray (Gy) and sievert (Sv), respectively.

Exponential Notation

There are a number of advantages to expressing results using powers of ten applied to the base and coherent derived SI units. First, it eliminates problems when values lie outside the range covered by the prefixes; second, it minimizes the possibility of computational mistakes; and third, it helps to indicate the number of significant figures in the value thereby reducing ambiguity (see Part II). Some examples of values expressed in SI units and this exponential notation follow:

$$\begin{aligned} 2810\ pCi \cdot L^{-1} &= 104\ Bq \cdot L^{-1} \\ &= 1.04 \times 10^{2}\ Bq \cdot L^{-1} \\ &= 1.04\ E{+}02\ Bq \cdot L^{-1} \end{aligned}$$

$$\begin{aligned} 12\ \mu R \cdot h^{-1} &= 3.1 \times 10^{-9}\ C \cdot kg^{-1} \cdot h^{-1} \\ &= 3.1\ E{-}09\ C \cdot kg^{-1} \cdot h^{-1} \end{aligned}$$

$$\begin{aligned} 123\ mrad &= 0.00123\ Gy \\ &= 1.23 \times 10^{--3}\ Gy \\ &= 1.23\ E{-}03\ Gy \end{aligned}$$

Conversion to SI Units

It obviously is neither feasible nor economically justifiable to completely and immediately change over from non-SI to SI units. This change will require familiarization and a transition period. Steps must be taken by both laboratories and regulatory agencies to aid and expedite this inevitable transition. This will only be achieved if there is a spirit of cooperation, adequate planning, and logical implementation by all those involved. At the same time, a number of initial steps taken during the transition would immediately further the goal of greater uniformity in data reporting practices.

It is therefore recommended that data reports be converted to the SI base and derived units as soon as technically and economically feasible. In many cases, this cannot be accomplished without changes in governmental regulations and data-reporting requirements imposed on laboratories. During the transition it is recommended that data reports include conversion factors between the SI and non-SI units, and whenever possible include the measurement results in both units. Since the scope of this change is much broader than the parochial scope of environmental radiation measurements data, efforts must be made by concerned laboratories, agencies, and organizations to implement simultaneous changes in all areas concerned with radiation quantities. Broad-based initiatives to plan and implement a safe and orderly transition are highly recommended.

Recommended Units for Use in Data Reporting

Whether temporarily sanctioned non-SI units (Ci, rad, etc.) or SI units (Bq, Gy, etc.) are employed, it is recommended that the number of combined units for radioactivity concentrations, exposure rates, etc., be immediately reduced to a smaller consistent set. The existing multiplicity of units in use is both needless and confusing.

It is recommended that radioactivity concentrations (except for effluent concentrations) be reported in units of activity per kg for mass measurements, and per m^3 or L for volume measurements. Recommended conventions are therefore:

1. Units for activity concentration in solid samples (e.g., soils, vegetation, etc.) should be $Bq \cdot kg^{-1}$ expressed in exponential notation (using the new SI units) or submultiples of $Ci \cdot kg^{-1}$ (using non-SI units).

2. Units for activity concentration in airborne particulate or gas samples should be $Bq \cdot m^{-3}$ expressed in exponential notation or submultiples of the $Ci \cdot m^{-3}$.

3. Units for activity concentration in liquid samples (e.g., water, milk, etc.) should be $Bq \cdot L^{-1}$ expressed in exponential notation or submultiples of $Ci \cdot L^{-1}$.

The recommended units for these activity concentrations and other radiation quantities, in terms of both the SI and non-SI units, are contained in Table 2. The table also illustrates the conversion factors (in E-notation) from the non-SI to SI units.

Additional Specifications

Obviously, additional specification of the results of measurements may be neessary. Measurements of solid sample, for example, will still require specification as to "dry weight" or "wet weight" and moisture content. Similarly, measurements of gas volumes require specification of the ambient temperature and pressure. One should always explicitly state all of the conditions that are necesssary for the results to be understood and interpreted unequivocally.

Other Unsatisfactory Current Practices

As stated initially, proper dimensioning of measurement results requires that the values and units be clearly understood and suitable for the value. There are a number of still unaddressed current practices that do not satisfy these basic criteria.

Perhaps one of the most serious is the failure to distinguish between measurements of "dose equivalent" and "absorbed dose." The abbreviation "dose" is continually, although incorrectly, used for both quantities. Oftentimes, the only way one can ascertain which is meant is by seeing if the values are reported in units of rems or rads. It should be apparent that not only must the measurement value be properly dimensioned, but the reported quantity itself must also be properly labelled.

A second major concern is the extensive reporting of "gross activity" ("total beta", "total gamma") measurement results in units of radioactivity. The inherent problems and abuses of such practices have been addressed previously[8]. These measurements contain no information on the identity of the radionuclides present in the sample. Therefore, no meaningful conclusions on the dosimetric significance of the results can be obtained. "Gross activity" measurements do serve a useful function for screening purposes to decide if additional, radionuclide-specific measurements should be made. Their value in data reports, however, can be seriously questioned. Reporting values of "gross activity" in units of Bq or pCi (or some other submultiple of the curie) is extremely misleading. At best, the result refers only to the activity that would be obtained from the observed counting rate for the standard radionuclide (that was used to obtain the counting efficiency). This conditional must be clearly described in any report of the result.

Recommendations

I.1 A consistent set of units for various environmental radiation quantities (for both SI and non-SI units) is contained within this guide (cf., Table 2) and should be employed for data reporting. The existing multiplicity in the number of units in use is both needless and confusing.

I.2 The use of the metric system, formally called the International System of Units (SI), and the use of standard metric practices and conventions should be encouraged. These units and recommended practices are briefly described within this guide. Additional details are available from more comprehensive sources referenced therein.

I.3 Data reports should convert to the SI base and derived units for radiation quantities as soon as technically and

TABLE 2
Recommended Units For Data Reporting

	In Non-SI Units a	In SI Units	Conversion Factor From Non-SI to SI Units b
Activity Concentrations (Environmental)			
Airborne Particulates and Gas	$pCi \cdot m^{-3}$	$Bq \cdot m^{-3}$	3.70E-02
Liquids (Water, Milk, etc.)	$pCi \cdot L^{-1}$	$Bq \cdot L^{-1}$	3.70E-02
Solids (Soil, Sediment, Vegetation, Foodstuff, etc.)	$pCi \cdot kg^{-1}$	$Bq \cdot kg^{-1}$	3.70E-02
Activity Concentrations (Effluent)			
Gas (Air)	$(\mu Ci \cdot mL^{-1})$*	$Bq \cdot m^{-3}$	3.70E+10
Liquid	$(\mu Ci \cdot mL^{-1})$*	$Bq \cdot L^{-1}$	3.70E+07
Exposure Rate (Environmental)	$\mu R \cdot h^{-1}$	$C \cdot kg^{-1} \cdot h^{-1}$	2.58E-10
Absorbed Dose	mrad	Gy	1.00E-05
Dose Equivalent	mrem	Sv	1.00E-05
Dose Equivalent Rate (Commitment)	$mrem \cdot yr^{-1}$	$Sv \cdot yr^{-1}$	1.00E-05

[a] Sanctioned for temporary use.

[b] To convert non-SI units to SI units, multiply the non-SI units by the conversion factor.

* Adopted because of established convention and use in Maximum Permissible Concentration (MPC) tabulations.

economically feasible. In view of existing governmental regulations and data-reporting requirements, it is, at present, neither feasible nor economically justifiable to completely and immediately change over from non-SI to SI units. This change will require familiarization and a transition period.

II. Significant Figures

The second requirement (outlined in the Overview) for reporting measurement data was that the reported value must be "expressed in an appropriate number of significant figures." Fortunately, this is nearly universally recognized, and is seldom a problem.

The "number of significant figures" refers to the number of numerical digits that is used to express the value. It is obvious that this number must be reasonable, and must not mislead or imply fictitious accuracy in the reported value. An "appropriate" number of digits (or significant figures) is that which is warranted by the accuracy of the reported value. That is, the appropriate number of digits to be retained in the reported value depends on the magnitude of the total uncertainty (see Part III) attached to this value.

For example, a reported value of 1.53365 E+12 Bq(41.45 Ci) for the quarterly tritium release from a nuclear facility is not reasonable. Surely no one would be fooled by the apparent implied accuracy of this value. Suppose further that the estimated total uncertainty in the value is +40%. Then, with the result expressed as

(1.53365 ± 0.61346) E+12 Bq
(i.e., 41.45 + 16.58 Ci),

the ludicrousness in the reportd value is even more apparent. This result should be reported as (1.5 + 0.6) E+12 Bq.

Similarly, suppose the annual release of radioactivity from several facilities at a site was reported (to two significant figures) as 21,000 Ci from one, 560 Ci from another, and 1.4 Ci from a third. To then say that the total activity released from the site was 21,561.4 Ci implies an accuracy in the measurement that is both incorrect and unintended.

Another, equally obvious, bad practice is the failure to ensure decimal agreement between the result and its associated uncertainty. For example, results such as 1.2 + 0.002 or 1.234 ± 0.2 are internally inconsistent. Either the result is more accurate than is given, as indicated by its associated uncertainty, and more significant figures should be retained; or the result is much less accurate than indicated, and the number of significant figures should be decreased to agree with the accuracy indicated by the quoted uncertainty. Care must therefore be taken in the number of significant figures reported both for the value itself and for the uncertainty term.

In general, environmental radiation measurements data seldom justify more than two or three significant figures for the value and one or two significant figures for the uncertainty. More significant figures should only be reported after careful consideration and a decision that the extra figures are indeed reportable. It is recommended that the uncertainty should be reported to no more than two significant figures, and the value itself should be stated to the last place affected by the qualification given by the uncertainty term.

For example, given a measurement result of 123.45 $\text{Bq}\cdot\text{L}^{-1}$ for an activity concentration with an estimated total uncertainty of ±12% (i.e., ±14.8 $\text{Bq}\cdot\text{L}^{-1}$), the result would be reported as

$$(1.23 \pm 0.15)\ \text{E+02 Bq}\cdot\text{L}^{-1}.$$

In this case, two significant figures for the uncertainty and three for the value might be justified. One might not wish to round the result to

$$(1.2 \pm 0.1)\ \text{E+02 Bq L}^{-1}$$

since the latter result implies a greater accuracy (approximately 8% compared to the original estimated uncertainty of +12%). The decision to report either two or three significant figures for a value is particularly critical when the value is close to running from one decade to another, such as for 89, 95, and 103. With estimated uncertainties of +15%, the above values would be reported as

89 ± 13
95 ± 14
103 ± 15

if two significant figures in the uncertainty term are retained. Otherwise, the values would be rounded to

90 ± 10
100 ± 10
100 ± 20.

The rules for rounding of numbers (i.e., the dropping of insignificant or unwarranted figures) are generally well known and available in a large number of sources [9, 10, 11, and 12], including elementary mathematics texts. These rules are summarized below:

1. To round off the number to n significant figures, truncate the number to n digits and treat the excess digits as a decimal fraction.

2. If the fraction is greater than or equal to 1/2, increase the least significant digit (i.e., the nth) by 1.*

3. If the fraction is less than 1/2 do not increase and leave the nth digit unchanged.

Similarly, rules for the number of significant figures to be retained in successive arithmetic operations have been developed [10, 11]. The rules for addition and subtraction differ from those for multiplication and division, and involve other assumptions (such as, that the values are independent and uncorrelated). Since no general rule can be given for all situations involving different types of arithmetic operations, a recommended procedure is to avoid rounding off until after the final calculation. This can be accomplished by treating all measurement values as exact numbers in the operations and to only round off the final result; or to carry two or more extra (insignificant) figures throughout the computation, and then to round off the final reported value to an appropriate number of significant figures [9]. Carrying along the extra insignificant figures will reduce the possibility of "rounding errors." This practice does not, however, excuse one from rounding the final result to an appropriate number of significant figures for the data reports.

These views are to a large degree currently incorporated into most data reporting practices and regulatory requirements.

Recommendations

II.1 A reported value should be expressed in an appropriate number of significant figures which is determined by the magnitude of the total uncertainty asssociated with the value.

II.2 The uncertainty should be reported to no more than two significant figures, and the value itself should be stated to the last place affected by the qualification given by the uncertainty term.

II.3 Care should be taken in the number of significant figures reported both for the value itself and for its associatd uncertainty. The value and its uncertainty must be in decimal agreement.

II.4 Reported values and their uncertainties should be rounded to an appropriate number of significant figures using the consistent, well-developed rules outlined in the text.

II.5 To avoid "rounding errors" in computations involving successive arithmetic operations, two or more extra (insignificant) figures should be carried on all the values throughout the computation, and then the final reported value should be rounded.

III. Treatment of Uncertainty Statements

Three of the most common abuses concerning the reporting of "errors" for environmental radiation measurements data were outlined in the Overview to this guide. These abuses shall be addressed in turn, but it may be useful to state, at the onset, the necessary conditions for avoiding their failings:

A REPORTED VALUE MUST INCLUDE AN ASSESSMENT OF ITS UNCERTAINTY.

THE REPORTED UNCERTAINTY MUST BE CLEARLY UNDERSTOOD AND MUST CONVEY SUFFICIENT INFORMATION SO THAT ITS MEANING, USING CORRECT TERMINOLOGY, IS UNAMBIGUOUS.

THE REPORTED UNCERTAINTY MUST BE BASED ON AS NEARLY COMPLETE AN ASSESSMENT AS POSSIBLE.

To help avoid ambiguity, the use of the words "error" and "uncertainty" (which are frequently used interchangeably) should be clarified. The word "error" has familiar usages which range from "a mistake" or "an oversight" to "a deviation from what is correct, right, or true," "the condition of having incorrect or false knowledge," and "the difference between a measured or computed value and a correct value." Further, its use in even the statistical sense is often confusing. Therefore, it is recommended that it not be used except:

1) in those cases where its meaning is unambiguous or of no portent, e.g., "absolute error";

2) when used in uniquely defined statistical terms, e.g., "standard error of the mean"; and

3) in commonly recognized phrases, e.g., "propagation of errors" or "statistical theory of errors."

As such the word "error" should be used as infrequently as possible. The word "uncertainty" is a preferred substitute which can be used to refer to the values following the ± symbol and all of its component parts (random and systematic uncertainties). Terms such as "uncertainty," "accuracy," etc. are more likely to be clearly defined, better understood, and unambiguously used. Data reports are less apt to be confusing if the frequent and loose use of "error" is avoided. This practice has been incorporated into this guide, and it is recommended that it be followed for all environmental radiation measurement data reports and documents.

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*This rule will introduce a slight rounding bias due to the treatment of the result when the fraction is exactly equal to 1/2. An unbiased procedure consists of incrementing the nth digit if it is an odd number (leaving the nth digit unaltered if it is an even number).

Consider now the necessary conditions, given above, for reporting an uncertainty.

A reportd value without an accompanying uncertainty statement is for nearly all purposes worthless. The value is rendered useless because it cannot be put to use with any confidence. Although the particular form of the uncertainty statement may be dependent on the intended or ultimate use of the result, it is without debate that the value must include one.

The absolute error or uncertainty of a reported value, which is the deviation from the true value, is unknowable because the true value can never be known exactly. Limits to this uncertainty, however, can be inferred and estimated from the measurement process itself. Foremost, the uncertainty should be a statement, based on a credible assessment, of the likely inaccuracy or the likely limits to the "absolute error" in the reported value. This uncertainty assessment also includes an incumbent risk of being incorrect.

Similarly, a reported value, say 15 ± 3 Bq, without further information is equally troublesome. The user would be forced to speculate whether the quoted 20% uncertainty is a standard error of the mean based on multiple measurements, or an estimated "statistical or counting error." Also unknown is whether it includes possible systematic uncertainties or is only the random uncertainty, and to what level of confidence the value can be ascribed. The possibilities are innumerable. In short, the user might ask: "How certain am I that the value is between 12 and 18 Bq?" To be useful, the uncertainty statement must convey sufficient information so that its meaning, based upon correct terminology, is unambiguous.

Suppose the above quoted uncertainty was reported as being a "counting error at 2 sigma (95%) confidence interval" [Cf., *Environmental Radiation Data*, quarterly compilations by the U.S. Environmental Protection Agency's Office of Radiation Programs]. Such reporting is certainly clearer. The user could infer that it is derived from an estimate of the standard deviation of the measurement or counting process (assuming it follows a Poisson distribution) taken to some higher confidence limit ("2 sigma").* This inference can be problematic however. First, although it is frequently assumed, twice the standard deviation is not necessarily a 95% confidence limit (see subsequent section on confidence limits). And second, the reported uncertainty is only an estimate of the random uncertainty or precision in the measurement process which does not address the accuracy of the value. The user might legitimately ask: "Is this the sole contribution to the overall uncertainty?"

Precision, Accuracy, Bias, and Random and Systematic Uncertainties

Precision and Random Uncertainty. The random uncertainty is a statement of precision (or more correctly, of imprecision) and is a measure of the reproducibility or scatter in a set of successive independent measurements [Ref. 13, p. 23-1]. Precision refers to the closeness of the set of results among themselves. When differences in the magnitudes of the observations are small, precision is said to be high; when the differences are large, precision is low. Random uncertainties are assessed and propagated by statistical methods. The treatment of these uncertainties is most familiar to physical scientists and those concerned with environmental radiation data.

Accuracy. The accuracy of a measurement process is a measure of the ability to obtain closeness to the true value. The absolute error of a particular result is just the difference between the measured or reported result and the true value. The exact difference of course is unknowable because the true value can never be known exactly. Although the absolute error is unknowable, limits to its magnitude can be inferred and estimated from the measurement process itself. The estimate of these limits to the absolute error is referred to as the uncertainty, and is used to estimate the inaccuracy of the measurement process.

Bias. A bias is a deviation from the true value which is always of the same magnitude and direction. It cannot be estimated or calculated from a given set of replicate measurements since each and every measurement is affected by the systematic bias in the same way [Ref. 13, p. 23-1 and Ref. 14]. There can be many contributing sources of bias in a given measurement process. They are introduced by the process and are characteristic of it. Such biases are not amenable to statistical treatments. They should be estimated upper limits for each conceivable (or assessable) source of inaccuracy in the measurement process. Their magnitudes would preferably be based on experimental verification, but may have to be estimated from experience and judgement.

The very familiar "bull's eye" example shown in Figure 1 should help illustrate the distinction between precision and systematic biases, and their relation to accuracy. The bull's eye of the target corresponds to the true value, and the six shots represent individual measurement results. The figure illustrates the concept of an inaccurate measurement due largely to imprecision, a precise but inaccurate measurement, and an accurate measurement. Inasmuch as accuracy requires precision, there is no such case as an accurate but imprecise measurement.

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*The term "sigma," in this case, is used incorrectly. Sigma is a parameter for the population, and should not be used to refer to the calculated sample statistic "standard deviation."

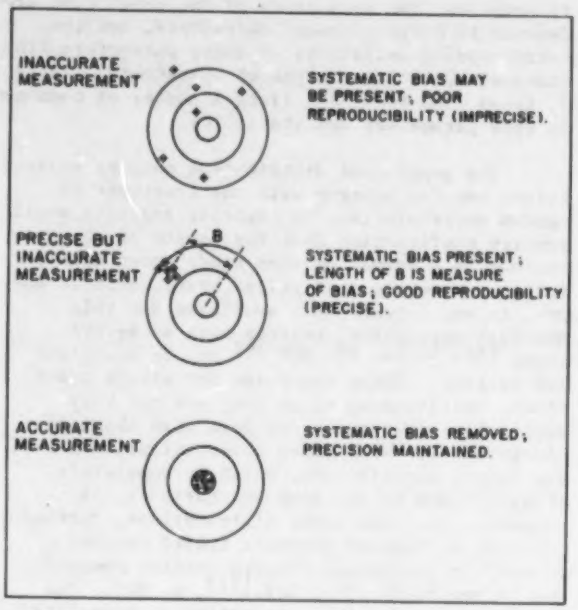

INACCURATE MEASUREMENT
SYSTEMATIC BIAS MAY BE PRESENT; POOR REPRODUCIBILITY (IMPRECISE).
PRECISE BUT INACCURATE MEASUREMENT
B
SYSTEMATIC BIAS PRESENT; LENGTH OF B IS MEASURE OF BIAS; GOOD REPRODUCIBILITY (PRECISE).
ACCURATE MEASUREMENT
SYSTEMATIC BIAS REMOVED; PRECISION MAINTAINED.

Figure 1. Illustration of the distinction between precision and systematic biases, and their relation to accuracy.

Systematic Uncertainty. For practical purposes, we may define systematic uncertainty to consist of those sources of inaccuracy which are biased, and those which may be due to random causes (stochastic processes) but cannot be or are not assessed by statistical methods. This broader definition which includes sources of inaccuracy in addition to biases is necessary to obtain a complete accounting of all sources of inaccuracy in the total uncertainty. It is the total uncertainty (obtained by combining the random and systematic components) that is ultimately used to estimate the inaccuracy.

"Blunders" and Data Rejection

Before proceeding to discussions of random and systematic uncertainties, it may be useful to consider the other source of inaccuracy. These are the outright mistakes or "blunders" in the measurement process. If one or more blunders are known to exist, then the value should be discarded, or a correction should be applied to the measurement. Parratt [Ref. 11, p. 69] described some possible blunders and their sources. A few examples which could easily be applied to environmental radiation measurements follow:

1. Incorrect logic, or misunderstanding what one is or should be doing. For example, applying a decay correction in the wrong direction.
2. Misreading of an instrument. Perhaps a field survey meter is an exigent situation, such as on a cold rainy day.
3. Errors in transcription of data which might occur in recording a scaler reading, transferring a value from one page to another, or even mis-entering a number into a calculator or computer terminal.
4. Calculational and arithmetical mistakes, which include misplaced decimal points, etc.

Interestingly, Parratt considered confusion of units and listing of an improper number of significant figures to be blunders.

One must recognize that blunders do and will occur. With an appreciation of this fact, every effort should be made to detect or avoid them. Many can be detected by establishing a system of independent checks on each stage of the measurement and data reduction system. A simple but effective system is an informal arrangement with a partner, colleague, or co-worker to check each other's work. It should include checking all stages of the data reduction (arithmetic, etc.) and an independent appraisal of the logic and the measurement process used to obtain the reported value. This checking is also useful in trying to assess all of the sources of systematic error. In effect, the checker serves as a "devil's advocate" to discover where the blunders may be.

Lastly, there is the question of rejecting suspicious or questionable data. When replicate results are available, standard statistical tests may be applied to decide if outliers should be rejected. Details on applying rejection tests can be found in Natrella [13, p. 17-1], Dixon and Massey [15], and other standard statistical texts. Although this is an acceptable practice, caution must be exercised. Rejection of data may result in an unrealistic self-consistent set and may actually bias the result. A further problem is that it may mask a real, anomolous and unexpected effect. Had Lord Rutherford's graduate students, Geiger and Marsden, applied data rejection tests to the small number of "unexpected" large scatterings in their α-particle scattering experiments, they might have failed to discover or interpret the existence of the atomic nucleus.

Jaffey[16] outlined three reasons why one should be conservative in rejecting moderate outliers:

a) Apparent patterns in sequences of random data are often startling. In the long run, averaging only bunched results gives averages that deviate more from true values than do means of all values.

b) As the number of measurements increases, the probability of an outlier increases.

c) In a large group of measurements, omission of the outlier has little effect on the average although it makes the data look better by decreasing scatter.

One of the purposes of environmental radiation surveillance is to detect (perhaps "unexpected") changes in trends. Judgement is necessary in order to avoid rejecting a result which in fact is an important effect. A practical guide is to let the suspicious result serve as a stimulant to find out what went wrong or what happened.

Statistical Treatment of Random Uncertainties

As described in the preceding section, random uncertainties are those which can be treated by statistical methods, and are derived from an analysis of replicate observations of a random or stochastic process. Numerous excellent sources on statistical theory are available [Cf., Ref 13 and 15] and should be consulted for greater detail or a more rigorous treatment. Only the results and a small amount of background information are presented here.

Before proceeding, some terminology is necessary. The term variate (or random variable) is used to denote the quantity which may take on any of the observed values. The agregate of these observations is termed a sample of some parent population, and may be described by a frequency distribution. This distribution of the population is a specification of the way in which the number of observations (frequencies) are distributed according to the values of the variates. The parameters of a population are the descriptive measures of the distribution. The mean (μ), a measure of the center or location of the distribution, and the standard deviation (σ) a measure of the spread or scatter of the distribution, are examples of parameters. The mean (μ) is also termed the first moment of the distribution, and the square of the standard deviation (σ^2), called the variance, is the second central moment. In the absence of an infinite population, one must make estimates of the parameters from finite populations (the sample of observations). A sample statistic is this estimator of the population parameter. The values of sample statistics are computed entirely from the sample and are the basic measures of the central tendency (location) and dispersion (variation). The mean ($\bar{x}$) and standard deviation (s) are widely known examples of statistics. Unfortunately, the distinction between population parameters and sample statistics is frequently ignored and the two are often confused, and incorrectly spoken of interchangably. The following diagram attempts to clarify the distinction.

STATISTICS		PARAMETERS
Calculated from sample (e.g., x and s^2)	$\longrightarrow$ used to estimate	for the population (e.g., μ and σ^2)

In practice, the parameters of the population are denoted by Greek alphabet characters, and the corresponding estimators of these parameters (the statistics) by Roman alphabet characters. Table 3, taken from Ref. [14] lists a number of commonly used parameters and statistics.

The population distribution must be known before one can proceed with the treatment of random uncertainties. A rigorous analysis would require confirmation that the sample of observations is a Normal or some other known distribution. Numerous statistical tests, such as the χ^2-, t- and F-tests, are available for this. Standard statistical sources such as References [11, 13 15, 16, and 19] may be consulted for details. These tests are not always practical, particularly since they are not very applicable with samples of less than about 30 observations. With fewer observations, a Normal (or Gauss) distribution, which is completely characterized by the mean and variance, is assumed. For some other distributions, further parameters, such as skewness (third central moment) or peakedness (fourth central moment), may be necessary [Cf., Ref. [11], p. 94]. The justification for this assumption of normality is based on precedent. The Normal distribution can be viewed as a mathematical result empirically shown to be valid for a large number of different experimental situations. It is still an assumption and it is well worthwhile to make a visual examination of the data for any marked departures from normality. There are some simple procedures to do this. They include construction of a histogram or graphical tests using probability paper [Cf., Ref. [17], p. 6-141 and Ref. [15], p. 55]. The discussion of random uncertainties which follows assumes that a Normal distribution is justifiable. It can be shown that this subsequent treatment is not absolutely dependent on a Normal population distribution. The Central Limit Theorem states this, provided the departures are not too great, and further predicts that the convolution or folding-together of non-Normal distributions tends to form Normal distributions. The probabilities for some typical intervals in the Normal distribution are provided in Table 4. As stated before, an analysis of the observed values will be used to estimate μ and σ^2.

Sample Mean and Standard Deviation. For n measurements of x, the best estimate of the parameter μ is obtained from the mean ($\bar{x}$) of the sample: and the best estimate of σ^2 from the variance ($s_x{}^2$), where

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \longrightarrow \mu \qquad (1)$$

$$\text{and } s_x{}^2 = \frac{1}{n-1} \sum_{i-1}^{n} \left(x_1 - \bar{x}\right)^2 \longrightarrow \sigma_x{}^2. \qquad (2)$$

TABLE 3

Population Parameters		Sample Statistics (Estimators of Parameters)
μ_x	(mean - first moment)	$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$
σ_x^2	(variance - second central moment)	$s_x^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})^2$
σ_x	(standard deviation of x about μ_x)	$s_x = \sqrt{s_x^2}$
$\sigma_{\bar{x}}$	(standard error of the mean, or standard deviation of the average)	$s_{\bar{x}} = \frac{1}{\sqrt{n}} s_x$
$\sigma_{xy} = \sigma_{yx}$	(covariance)	$s_{xy} = s_{yx} = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$
$\frac{\sigma}{\mu}$ (100)	(coefficient of variation, or relative standard deviation, expressed in per cent)	$v_x = \frac{s_x}{\bar{x}}$ (100)

The sample standard deviation is the square root of the variance or the quantity s_x. It refers to the standard deviation computed from a sample of measurements.

TABLE 4

Interval $(\mu-\zeta\sigma_x)$ to $(\mu+\zeta\sigma_x)$	Probability of x having a value within this interval.
ζ	%
0.6745	50.
1.000	68.269
1.960	95.
2.000	95.450
2.576	99.
3.000	99.73

Standard Error of the Mean. Any mean $\bar{x}$ is determined from a finite number of measurements. If the determination is repeated, one can obtain a series of slightly different $\bar{x}$ values. According to the Central Limit Theorem, for large n, the distribution of these $\bar{x}$ values will be close to Normal for any distribution of x. Thus, a standard deviation of this distribution could be obtained from repeat determinations of $\bar{x}$. It may, however, also be estimated from just the measurements used in a single determination of x. This estimate of the precision on the mean is termed the standard error of the mean ($s_{\bar{x}}^2$) which is given by

$$s_{\bar{x}}^2 = \frac{s_x^2}{n} = \frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2. \qquad (3)$$

The quantity $s_{\bar{x}}^2$ is termed the variance of the mean. The standard error of the mean ($s_{\bar{x}}$) must not be confused with the sample standard deviation (s_x). The standard deviation s_x is only dependent on the measurement precision, while $s_{\bar{x}}$ depends on both the precision and the number of observations.

Propagation of Random Uncertainities (Measurements Involving Several Physical Quantities). The uncertainties that have been described up till now are those derived by statistical methods from replicate measurements. A reported value is seldom measured directly, and its associated total random uncertainty is usually not entirely due to random fluctuations made just during that measurement. The reported value may be derived from quantities that were constant during the measurement (e.g., an instrument calibration factor) or from several measured quantities. These quantities, including contants, have uncertainties in their numerical values due to random causes. Estimates of their uncertainty may have been previously derived from replicate measurements at the time the values were determined. It is necessary to combine (or propagate) these individual contributions into a total random uncertainty term for the reported value.

The statistical theory of errors to combine the separate variances of the quantities involved is usually based on the assumption of Normal distribution functions. This results in the very familiar "propagation of error formula" which is based on just the first order Taylor series expansion of the functional form of x about the mean of x (see Ku [20] for a derivation and greater detail). If the reportd value of x is determined by a combination of independent variables, u, v, w. ... which is given by

$$x = f\,(u, v, w, \ldots), \tag{4}$$

then the estimated variance on x is

$$s_x^2 = \left(\frac{\partial f}{\partial u}\right)^2 s_u^2 + \left(\frac{\partial f}{\partial v}\right)^2 s_v^2 \tag{5}$$

$$+ \left(\frac{\partial f}{\partial w}\right)^2 s_w^2 + \ldots + \begin{matrix}\text{covariance}\\ \text{terms}\end{matrix}$$

where s_u^2, s_v^2, s_w^2, ... are the estimated variances on u, v, w, respectively. The partial derivatives are evaluated with all other variables fixed at their mean values. For simplicity, let αi correspond to the entity $(\partial f/\partial i)^2 s_i^2$ for the ith component. Then,

$$s_x^2 = \sum_i \alpha i \tag{6}$$

This treatment assumes that the terms of higher order than the first partial derivatives are negligible,* and that all of the component quantities are independent and not correlated to each other. This is frequently the case, but not necessarily always true. For details of treating partially correlated components, the reader is referred to Ku[20] or other standard statistical sources. It is always necessary to consider the basic functional form of the component variables before assuming a particular propagation formula. Error propagation formulae for some simple, common functions are provided in Table 5.

Grand Averaging and Weighted Means. The preceding discussion concerned only the calculation and propagation of mean values and their variances from a set of independent measurements of the same quantity. Frequently, one may have estimates of the variance on each individual value in the set. This may arise from estimates of the "counting errors" derived from the total number of counts in single determinations (as will be described shortly), or when computing grand averages of previously averaged values where a variance was calculated for each individual mean. In this case, one may intuitively feel that the averaging process should be performed by giving greater weight to those values that have greater precision. It can be shown (Cf., Ref.[21], p. 44) that for a set of m independent values of quantity x (all taken from the same population), each with mean $\bar{x}_j$ and variance s_{xj}^2 the best estimate of the population mean is obtained with a weighting factor of $1/s_{xj}^2$ for each x_j. Thus, the overall mean (grand average) is given by

$$\bar{\bar{x}} = \frac{\sum_{j=1}^{m} \bar{x}_j/s_{x_j}}{\sum_{j=1}^{m} 1/s_{x_j}^{\,2}} \tag{7}$$

The use of this weighting factor results in a mean that has the least variance. This variance is

$$s_{\bar{x}}^2 = 1/\sum_{j=1}^{m} 1/s_{x_j}^{\,2} \tag{8}$$

This treatment is not applicable if any of the xj values are correlated to any of the others. Therefore, weighting factors, which are based on the reciprocals of individual uncertainties, must not include any contribution from systematic biases, but only those uncertainties due to independent random causes. One could have, just as well, grand averaged the results without weighting. That is,

$$\bar{\bar{x}} = \frac{1}{m} \sum_{j=1}^{m} \bar{x}_j \quad , \tag{9}$$

with

$$s_{\bar{x}}^2 = \frac{1}{m(m-1)} \sum_{j=1}^{m} (\bar{x}_j - \bar{\bar{x}})^2 \tag{10}$$

---

*This is based on the assumption that over the range of the variables given by their errors, only small changes in the partial derivatives occur. If the errors are large, the second partial and partial cross derivatives should be included. Cf., Ku[20].

This latter approach results in a mean that does not have the least variance. It can, however, serve as a useful guide. In general, one should always treat with suspicion any result that has a significantly different weighted and unweighted mean.

Statistics of Radioactive Decay (Poisson Distribution). In addition to the usual random uncertainties associated with replicate observations (discussed above), radioactivity measurements are also subject to a random variation arising from the nature of the radioactive decay process itself. The rate of radioactive decay is not a constant with time, but fluctuates randomly about a mean or expectation value. This decay can be described by the Poisson probability distribution function (see Ref. [14] and references therein for a derivation of the Poisson function as a limiting case of the Binomial or Bernoulli distribution).

The Poisson assumption allows one to estimate, from a single measurement, the spread or scatter of a measured number of counts (c) about the mean value η. Assuming that the total number of counts c obtained in the measurement is the best estimate (or is a good estimate of

TABLE 5

Propagation of Error Formulas for Some Simple Functions

Function Form†	Approximate variance	Additional term if u and v are correlated
$x = au \pm bv$	$s_x^2 = a^2 s_u^2 + b^2 s_v^2$	$\pm 2ab s_{uv}$
$x = auv$	$\frac{s_x^2}{x^2} = \frac{s_u^2}{u^2} + \frac{s_v^2}{v^2}$	$2 \frac{s_{uv}}{uv}$
$x = \frac{au}{v}$	$\frac{s_x^2}{x^2} = \frac{s_u^2}{u^2} + \frac{s_v^2}{v^2}$	$-2 \frac{s_{uv}}{uv}$
$x = u^2$	$s_x^2 = 4 u^2 s_u^2$	
$x = \sqrt{u}$	$s_x^2 = 1/4 \frac{s_u^2}{u}$	
$x = au^{\pm b}$	$\frac{s_x^2}{x^2} = b^2 \frac{s_u^2}{u^2}$	
$x = ae^{\pm bu}$	$\frac{s_x^2}{x^2} = b^2 s_u^2$	
$x = cu^{\pm a} v^{\pm b}$	$\frac{s_x^2}{x^2} = a^2 \frac{s_u^2}{u^2} + b^2 \frac{s_v^2}{v^2}$	$2(\pm a)(\pm b) \frac{s_{uv}}{uv}$
$x = \ln u$	$s_x^2 = \frac{s_u^2}{u^2}$	
$x = a \ln(\pm bu)$	$s_x^2 = a^2 \frac{s_u^2}{u^2}$	

---

†Where a, b and c are constants; u and v are assumed to be statistically independent; and the value of x if finite and real [e.g., $v \neq 0$ for ratios with v as denominator, $u > 0$ for $\sqrt{u}$ and ln u, and $(\pm bu) > 0$ for $\ln(\pm bu)$].

the mean value that would be obtained from a large number of replicate measurements) of the mean value η , i.e.

$$c \longrightarrow \eta ,$$

then the best estimate of the standard deviation in η may be calculated by

$$s_c = \sqrt{c} \longrightarrow \sigma_\eta = \sqrt{\eta} \qquad (11)$$

where the arrows are read as "used to estimate." Since the counting rate (r) measured over a given counting time T is determined by c, the mean rate (r) and its standard deviation are estimated by

$$r = \frac{c}{T} \qquad R = \frac{\eta}{T} , \qquad (12)$$

$$\text{and } s_r = \frac{\sqrt{c}}{T} \qquad \sigma_R = \frac{\sqrt{\eta}}{T} \qquad (13)$$

The relative standard deviation in r (s_r/r) obviously decreases with increasing total number of counts. Similarly, an increase in the counting time of a source with a given rate, decreases s_r.

Background Subtraction. For most environmental radiation measurements, the counting rate of a source (r_s) is determined by subtracting a background rate (r_b) from a gross (source plus background) rate. That is,

$$r_s = r_{s+b} - r_b .$$

By the propagation of errors, as described earlier, the standard deviation in r_s is estimated by

$$\left.\begin{aligned} s_{r_s} &= \sqrt{s_{r_{s+b}}^{\;2} + s_{r_b}^{\;2}} \\ &= \sqrt{\frac{r_{s+b}}{T_s} + \frac{r_b}{T_b}} \\ &= \sqrt{\frac{c_{s+b}}{T_s^{\,2}} + \frac{c_b}{T_b^{\,2}}} \end{aligned}\right\} \qquad (14)$$

where T_s and T_b refer to the gross and background counting times, respectively. These and similar equations which can be derived form the basis for the experimental design of radioactivity measurements (e.g., optimizing the division of time between T_s and T_b. See, for instance, Ref. [14] and [21] for greater details on radioactivity measurement procedures and processing of counting data.

Random Uncertainty Components. The standard deviations described above, which are estimated from the total number of counts in a single determination of the counting rate, are usually termed the "counting errors." Although the use of this term will probably continue to prevail, the term is a misnomer. It takes into consideration only the random scatter about the mean from the radioactive decay process itself. To presume that this is the only source of random fluctuation in the overall measurement or counting process is fatuous. Unfortunately, federal guidance, as it pertains to reporting environmental radiation data, does not suggest otherwise. Other sources may be random timing uncertainties, random variations in the sample preparation, positioning of the sample at the detector, etc. The list is nearly endless. Some of these are addressed in Ref. [1].

The only way to realistically assess the overall random uncertainty is to make replicate determinations and calculate the standard deviation (or variance) of the mean by the usual statistical methods (e.g., by Eq. 2). For reported values derived from several component quantities, the individual uncertinty estimates (obtained from replicate measurements for each independent variable) must be propagated (e.g., by Eq. 5) to obtain the overall standard deviation (or variance) of the final value.

It is recognized that replicate measurements of environmental samples are uncommon and may not be feasible because of time and cost constraints. Yet an uncertainty assessment based on some procedure beyond calculating the square root of the total number of counts is clearly needed. A number of procedures, such as the Poisson index of dispersion test, are available to test for the presence of extraneous measurement variations beyond that inherent in the radioactive decay process itself (Cf., Ref. [14]; Ref. [16]; Ref. [22], p. 789; Ref. [23], p. 64). Again, such tests require multiple measurements, at least occasionally, to assess the magnitude of the overall variability from all random causes. Various control charts (Cf. Natrella [13], p. 18-1 and Ref. [24], p. 32) can also be used as a continuous graphical record of this variability. It must be emphasized, however, that these estimates of random uncertainty should not be based exclusively on the information derived from just the present measurements. Presently derived information should be added to the information accumulated in the past on the variability of the measurement process. In this way, more realistic and reliable canonical values of the random uncertainty estimates may be established over time. Ideally, every major step or component of the measurement process should be independently assessed. This would include not only the variability inherent in the particular measurement of concern but also the imprecision arising from corrections, constants, calibration factors and any other measurements that make up the final result.

A practical procedure for making a more complete uncertainty assessment will be discussed later. So far, we have only addressed the calculation of statistics (e.g., the standard deviation) from replicate measurements, and the estimation of the Poisson counting error from a single measurement. In either case, in order to utilize these pieces in an overall uncertainty estimate, we need to consider the assessment of systematic uncertainties.

Assessment of Systematic Uncertainties

The distinction between random and systematic uncertainties was demonstrated earlier. In practice, the systematic uncertainties can be considered to be those sources of inaccuracy which are biased and not subject to random fluctuations, and those which may be due to random causes but can not be or are not assessed by statistical methods. Although a general guideline for the approach to the assessment can be formulated, there are, unfortunately, no rules to objectively assign a magnitude to the systematic uncertainties. For the most part, it is a subjective process. Their magnitudes would preferably be based on experimental verification, but may have to rely on the judgement and experience of the experimenter. The general approach is:

Step 1

Consider and identify all of the conceivable sources of inaccuracy. This requires a careful scrutiny of every detail and aspect of the measurement that can affect the reported value. The "devil's advocate" can be a useful aid in this step.

Step 2

From the above set, extract the blunders and those sources which can and have been (or will be) assessed by statistical methods (i.e., the random uncertainty contributions).

Step 3

Assign a magnitude to the conceivable limit of uncertainty for each of the remaining sources.

There are at least two general reference frames for estimating the magnitude of the systematic uncertainties. One is to consider them as upper bounds, overall or maximum limits[25]. The other is to express them in terms of some probability (e.g., the limits in which the true value is expected to lie in two out of three cases). The latter approach is not recommended since it implies some knowledge of their probability distribution, which is not likely [26].

In general, each systematic uncertainty contribution is considered as a quasi-absolute upper bound, overall or maximum limit on its inaccuracy value. Its magnitude is typically estimated in terms of a semi-range of plus or minus δ about the mean of the measurement result. If the reported value or mean x is determined by a combination of independent variables [as in Eq. (4)]

$$x = f(u, v, w, \ldots\ldots),$$

then the relative contribution to the systematic uncertainty in x due to the estimated systematic uncertainty in one of the variables (δ_u) is

$$\delta = \left(\frac{\partial f}{\partial u}\right)^2 \delta_u{}^2 \qquad (15)$$

(assuming that the variables are independent of each other).

By what method then should the magnitude of these maximum limits to the systematic uncertainties be asigned? It may be based on a comparison to a standard or verification with two or more independent and reliable measurement methods. Additionally, it may be

based on judgement;

based on experience;

based on intuition;

based on measurements and data (e.g., by "varying the factor at issue to its extreme range and noting the change on the results"[27]; or comparison to other methods of measurement, other instruments, etc.[14]; or just a pure guess[28] (which is not recommended, but may be better than nothing).

Or it may include combinations of, or all of the above factors.

The fact that a conceivable source of inaccuracy is ascribable to random causes is not a sufficient condition for treating it as a random uncertainty in error reporting. It must be assessable by statistical methods derived from an analysis of repeated measurements. In the absence of these data, the effect of this random cause must be treated as a systematic uncertainty. A program to design and execute experiments (Cf., Ref.[13, 14, and 29] for statistical designs of experiments) to determine the effects of all such factors and considerations requires resources beyond the capacity of most laboratories. Yet a conscientious effort must be made to assess every source of inaccuracy.

The process of assessing the systematic uncertainties is not a simple task. Because of the complexity and its rather subjective nature, it has frequently been ignored. This has resulted in optimistic and underestimated overall uncertainty assessments. It is due as much to overlooking and ignoring possible sources of inaccuracy, as to underestimating those that are known. To aid the experimenter in this process, a list of conceivable sources of inaccuracy and some suggestions to treat them is provided in Ref.[1].

Confidence Limits

The net result from a single counting experiment (x) or the calculated mean from multiple measurements ($\bar{x}$) is used as the best estimate of the population parameter μ_x and hence the true value (in the absence of bias). Because of the associated statistical fluctuations about x or $\bar{x}$, it may not be exactly equal to μ_x. The confidence interval is the range of possible values on either side of x or $\bar{x}$ within which μ_x can be expected to fall. Confidence limits are the numerical values at the limits of this range. The parameter μ_x can be expected to lie within the confidence limits with a given probability. This probability, usually expressed as a percentage, is called the confidence coefficient.* Alternatively, the confidence coefficient can be considered to be the probability that the confidence interval will include the parameter μ_x. These concepts are illustrated below for a mean of $\bar{x}$. When addressing the subject of confidence limits, what is sought is a procedure to calculate the confidence limits for a given confidence coefficient (probability), or to determine the probability for some confidence interval.

Confidence Limits for Systematic Uncertainty. As discussed in the preceding Section, a systematic uncertainty is an estimated upper or maximum bound for each conceivable and assessable contributing systematic source of inaccuracy. That is, there is a high degree of confidence (high likelihood or large probability) that the systematic uncertainty due to this contributing source of inaccuracy would not exceed the numerical value of this stated systematic uncertainty. Therefore, a systematic uncertainty which is estimated in terms of a semi-range may be regarded as a 99% or greater confidence interval. Although the entire subject of systematic uncertainty is characterized by an uneasy nebulousness, the above approach, which is unsupported by statistical or physical principles, does contain a degree of decisiveness. One can hardly argue that a better estimate than that provided by the conscientious experimenter is obtainable.

Confidence Limits for Random Uncertainty (Normal Distribution). Fortunately, one can rely on statistical theory when considering the confidence limits for random uncertainties. A common practice is to express the confidence limits in terms of

CONFIDENCE LIMITS

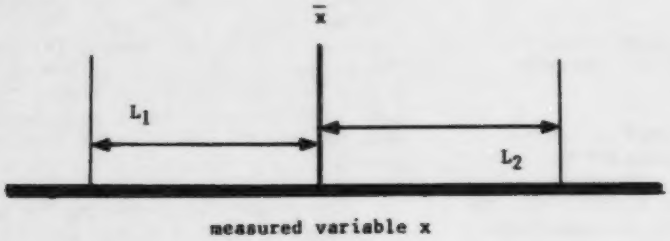
are the values $(\bar{x} - L_1)$ and $(\bar{x} + L_2)$

CONFIDENCE INTERVAL

is the set of possible values between $(\bar{x} - L_1)$ and $(\bar{x} + L_2)$

CONFIDENCE COEFFICIENT* (P)

is the probability (in %) that μ_x will lie within the confidence interval or between the confidence limits



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*The confidence coefficient is often referred to as the "confidence level". Although the latter usage is probably more familiar to most readers, it is in conflict and often confused with the term "significance level" which is employed in all statistical literature. The confidence or significance (α) associated with the specification of a confidence interval is the probability that the interval will not include the true value. The confidence coefficient (1-α), which is often expressed as a percentage P, is the term used to describe the probability that a confidence interval will include the true value. For example, a 95% confidence interval is one for which the confidence coefficient (P), not the significance level (α), is 95%. In this case, the significance level is 5%. To avoid this confusion, the term "confidence level" is deliberately avoided and, therefore, not employed.

some multiple of the standard deviation or standard error of the mean. For results from multiple measurements, the confidence limits for the mean μ may be expressed in terms of some integral multiple of the calculated standard deviation s_x, i.e.,

$$\bar{x} \pm s_x \;,$$
$$\bar{x} \pm 2s_x \;,$$
$$\bar{x} \pm 3s_x \;, \text{ etc.}$$

If the estimated statistic s_x was derived from a large number of measurements n, and if the distribution of x values is Normal, then these are 68.3%, 95.5% and 99.7% confidence intervals, respectively. It must be emphasized that these confidence coefficients apply only when n is very large and when the distribution is Normal. As the number of measurements n decreases, the confidence coefficient or probability that x lies within a given confidence interval gradually diminishes. Table 6, taken from [25], demonstrates the effect of various values of n on the confidence coefficients. In order to determine the magnitude of a confidence interval $(L_1 + L_2)$ at a given confidence coefficient (P), we need to first consider the number of measurements or what is termed the number of degrees of freedom.

Degrees of Freedom. For purposes of this guide, the number of degrees of freedom (ν) for a calculated statistic (e.g., s_x) is the number of measurements (n) in excess of those needed to determine the estimate of the population parameter of interest. For example, previously we noted that the precision on the mean ($\bar{x}$) may be estimated in terms of the standard error of the mean ($s_{\bar{x}}$). Recalling the definition of the variance, given by Eq. (2), the number of degrees of freedom in $s_{\bar{x}}$ is the number of independent terms in the residual sum of the squares, $\sum_{i=1}^{n} (x_i - \bar{x})^2$. Thus, in calculating the mean of n observations, the number of degrees of freedom (ν) in $s_{\bar{x}}$ is (n-1).

If $\bar{x}$ is derived from a combination of more than one variable [see Eq. (5)], the number of degrees of freeedom does not have an exact meaning. An approximation, derived by Welch[30], can be used to obtain an effective number of degrees of freedom (ν_{eff}) in $s_{\bar{x}}^2$. This is given by

$$\frac{1}{\nu_{eff}} = \frac{\sum_i a_i^2/\nu_i}{\sum_i a_i^2} \tag{16}$$

where ν_i is the number of degrees of freedom in $s_{\bar{x}}$ for the ith component of a_i is defined by Eq. (6). The value of ν_{eff} calculated in this way is sufficiently accurate in most applications. When ν_i for the individual components becomes small, the approximation becomes less valid[31]. Examples illustrating this type of calculation for n measurements of a sample and k measurements of a standard are provided in NCRP Report 12[32].

Confidence Limits for Random Uncertainty (t-Distribution). With a value of ν (or ν_{eff}) and $s_{\bar{x}}$ for a mean x, one can determine the confidence interval for any given confidene coefficient P. The confidence interval about the mean $\bar{x}$ is symmetrical for a Normal distribution, and the confidence limits may be calculated by

$$L_1 = L_2 = t_\nu(P)s_{\bar{x}} \tag{17}$$

where t is the Student t- value for a confidence coefficient P and ν degrees of freedom. Table 7 contains values of the t-statistic as a function of ν for various values of the confidence coefficient P. When more than one variable is involved, the value of ν_{eff} [from Eq. (16)]

TABLE 6

Confidence coefficients P for the s_x, $2s_x$ and $3s_x$ confidence intervals for the Normal distribution with various values of n[16].

CONFIDENCE INTERVAL	CONFIDENCE COEFFICIENT (P) IN %			
	n=5	n=10	n=20	n=∞
$\bar{x} \pm s_x$	62.6	65.7	67.0	68.269
$\bar{x} \pm 2s_x$	88.4	92.3	94.0	95.450
$\bar{x} \pm 3s_x$	96.0	98.5	99.3	99.730
$\bar{x} \pm 4s_x$				99.994

is usually fractional. The value of t may then be obtained from the table by interpolation, or ν_{eff} may be rounded down to the next integral value. Thus, the random uncertainty could be expressed, in terms of the calculated or propagated s_x and ν, as the confidence limits ($\pm ts_x$) for a given confidence coefficient P. As before, this process of going to higher confidence intervals requires an assumption about the form of the distribution, and is dependent on the number of measurements. Table 7 illustrates that the common practice of equating $3s_x$ with the 99% confidence interval is erroneous for ν less than about 9 or 10.

Confidence Limits for Random Uncertainty (Poisson Distribution). An analogous situation exists when considering the confidence limits for the Poisson counting error from single determinations. In this case, one assumes the counting process can be described by a Poisson distribution, and the dispersion statistic (e.g., the standard deviation) is estimated from the number of counts obtained in the measurement [such as by Eqs. (11), (13), and (14)]. As described before, the Poisson distribution approximates the Normal for very large counts (>100). Then, the confidence limits for the number of counts c could be given by

$$L_1 = L_2 = t_\infty(P)\sqrt{c} \qquad (18)$$

where t_∞ is the Student-t value for infinite degrees of freedom corresponding to a given confidence coefficient for the Normal distribution. Such as, t is 1.96 and 2.58 for the 95% and 99% confidence coefficients, respectively (refer to Tables 4 and 7). This estimate will, of course, be more correct the larger the number of counts. For small numbers of counts, the Poisson distribution no longer approximates the Normal very well; the confidence limits become asymmetrical and the approximation by Eq. (18) poorly estimates the confidence interval. For example, the lower and upper confidence limits for a low number of counts c may be given by ($c-L_1$) and ($c+L_2$), respectively where

TABLE 7

Student t-Values Corresponding to a Given Confidence Coefficient P for Use with an Estimated Standard Deviation for a Normal Distribution Based on ν Degrees of Freedom.

P= ν	68.269%	95.000%	95.450	99.000	99.730%
1	1.837	12.706	13.968	63.657	235.80
2	1.321	4.303	4.527	9.925	19.207
3	1.197	3.182	3.307	5.841	9.219
4	1.142	2.776	2.869	4.604	6.620
5	1.111	2.571	2.649	4.032	5.507
6	1.091	2.447	2.517	3.707	4.904
7	1.077	2.365	2.429	3.499	4.530
8	1.067	2.306	2.366	3.355	4.277
9	1.059	2.262	2.320	3.250	4.094
10	1.053	2.228	2.284	3.169	3.957
11	1.048	2.201	2.255	3.106	3.850
12	1.043	2.179	2.231	3.055	3.764
13	1.040	2.160	2.212	3.012	3.694
14	1.037	2.145	2.195	2.977	3.636
15	1.034	2.131	2.181	2.947	3.586
16	1.032	2.120	2.169	2.921	3.544
17	1.030	2.110	2.158	2.898	3.507
18	1.029	2.101	2.149	2.878	3.475
19	1.027	2.093	2.140	2.861	3.447
20	1.026	2.086	2.133	2.845	3.422
25	1.020	2.060	2.105	2.787	3.330
30	1.017	2.042	2.087	2.750	3.270
40	1.013	2.021	2.064	2.704	3.199
60	1.008	2.000	2.043	2.660	3.130
120	1.005	1.980	2.023	2.617	3.069
∞	1.000	1.960	2.000	2.576	3.000

Adapted from Brian L. Joiner, "Student t-Deviate Corresponding to a Given Normal Deviate," J. Res. NBS 73C, 15 (1969); and CRC Handbook of Mathematical Tables, First Ed. Chemical Rubber Publishing Co., Cleveland, Ohio (1962), p. 271.

$$L_1 = \tau_1\sqrt{c}$$

$$\text{and } L_2 = \tau_2\sqrt{c} \tag{19}$$

Values of τ as a function of the number of counts for confidence coefficients of P=68%, P=95%, and P=99% are illustrated in Figure 2 and tabulated in Table 8. As indicated, for low counts, (under 100 or so), the Normal approximation of Eq. (18) can give a result which is in error. As a result, special tables [33] are needed to obtain appropriate confidence limits for small numbers of counts.

From Eq. (15) it follows that, for a counting rate r_s with standard deviation s_{r_s}, the confidence limits for a higher confidence coefficient P would be given by $r_s \pm L$ where

$$L = \sqrt{\tau_{c_{s+b}}(P)s_{r_{s+b}}{}^2 + \tau_{c_b}(P)s_{r_b}{}^2}$$

$$= \sqrt{\tau_{c_{s+b}}(P)\frac{c_{s+b}}{T_s{}^2} + \tau_{c_b}(P)\frac{c_b}{T_b{}^2}} \tag{20}$$

Or, alternatively, the τ values in Eq. (20) could be replaced with values of t_∞ when the Normal approximation is valid (i.e., very large counts).

In summary, any consideration of confidence limits for single determination or multiple measurement situations is, first, distribution dependent requiring an assumption about the underlying population distribution; and second, is size dependent requiring knowledge of the number of measurements, degrees of freedom or magnitude of the counts, etc.

Reporting the Overall Uncertainty

If the reported uncertainty is to be a credible assessment of the likely accuracy, it must be based on as nearly a complete an assessment as possible and must consider all conceivable sources of inaccuracy.

Categorization of the Random and Systematic Uncertainty Components. A clear distinction between random and systematic uncertainties is often difficult and troublesome. In part, this is because many experimental processes embody both systematic and stochastic (random) elements.

In general, the random uncertainty contributions can be considered to be those sources of inaccuracy which can be and are assessed and propagated by statistical methods. Estimates of population parameters, or statistics, are computed entirely from the measurements data.

The systematic uncertainty components can be considered to be the conceivable sources of inaccuracy which are biased and arise from non-stochastic systematic effects, as well as those which may be due to random causes but can not be or are not assessed by statistical methods. Hence, it is meaningful to speak of a random uncertainty contribution only if one has a computed statistic for the magnitude of the random variation. Further, this does not imply that every conceivable source of inaccuracy (say, the chemical yield) lies in either just the random or systematic uncertainty category. One might obtain an estimate of the random uncertainty contribution by calculating a standard deviation from the results of multiple determinations of the chemical yield, and

TABLE 8

Values of τ Corresponding to a Given Confidence Coefficient P for use with an Estimated Standard Deviation for a Poisson Distribution.

COUNTS	P=68%		P=95% *		P=99%*	
	τ_1	τ_2	τ_1	τ_2	τ_1	τ_2
1	0.83	2.29	0.975	4.57	0.995	6.43
4	0.95	1.60	1.46	3.12	1.66	4.30
9	0.97	1.37	1.63	2.69	1.96	3.67
16	0.98	1.28	1.71	2.50	2.11	3.37
25	0.98	1.22	1.76	2.38	2.20	3.20
50	0.99	1.15	1.82	2.25	2.31	3.01
∞	1.00		1.96		2.58	

* Adapted from E.S. Pearson and H. O. Hartley, Biometrika Tables for Statisticians, Vol. 1, Cambridge Univ. Press (1954), Table 40.

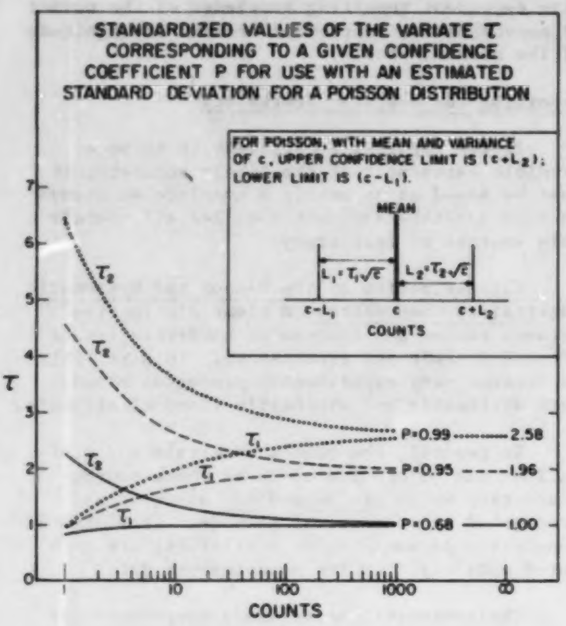


Figure 2.

still have a systematic uncertainty in the chemical yield due to a bias in all of the mass measurements made in the determination of the yields. The diagram below attempts to illustrate the concept of making a complete assessment of all of the conceivable sources of inaccuracy, and their division between random and systematic components.

Total Random Uncertainty. From preceding sections, we can obtain a combined total random uncertainty contribution, stated in terms of some dispersion statistic, such as the standard deviation s_x for a measurement result x. The value of s_x may be evaluated from the results of multiple measurements using, for example, Eq. (3). The Poisson counting error contribution may be estimated from Eq. (13), (14) or comparable equations. Except for this contribution which may be evaluated from single measurements (due to the Poisson assumption), all other contributions must be evaluated by calculating statistics from the results of replicate determinations. As noted, control charts may aid this process. The total random uncertainty, s_x, would include not only the Poisson counting error and randum uncertainty derived from the particular measurement under concern, but also the random components from corrections, constants, calibration factors and any other measurements that also make up the final result x. These contributions may be combined by propagation of error formulae, such as Eq. (5).

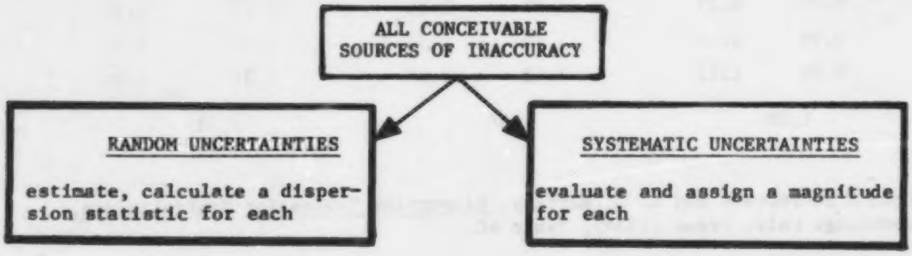
Conceptually, one can propagate and express the total random uncertainty in terms of some confidence limits at any chosen confidence coefficient. This requires a number of assumptions, such as to the underlying population distributions, and can very rapidly become exceedingly complicated requiring computations based on the number of measurements involved in each random uncertainty component, the number of degrees of freedom, the magnitude of the counts in the counting error contribution, etc. One is therefore confronted with the choice between making simplifying assumptions (which ultimately may provide results that are misleading), or performing complex calculations (whose efficacy, in terms of the time and cost required can be seriously questioned).

Systematic Uncertainty Components. Lastly, we can obtain a list of each conceivable source of systematic uncertainty expressed as a confidence limit ($\pm\delta_j$ which can be considered to correspond to some 99% or greater confidence interval.

Approaches to an Overall Uncertainty Statement. One must now consider 1) to what confidence coefficient should the total random uncertainty s_x be reported; 2) how should the individual systematic uncertainty components (δ_j) be combined; and 3) how should the random and systematic uncertainties be combined to form an overall uncertainty. All three questions are interrelated. Underlying this entire discussion is the fundamental consideration that the way uncertainties are reported is dependent on their intended or ultimate use.

Methods of Combining the Random and Systematic Uncertainty Components. Purists would argue that it is incorrect from a theoretical point to view to combine random and systematic uncertainties in any fashion [34]. Their approach is to separately state the random and systematic uncertainty components. For the random contribution, this is to include the confidence limits, the confidence coefficient, and the number of degrees of freedom. For the systematic uncertainty contribution, each component is to be listed, and the method of combination clearly stated. This approach requires a detailed uncertainty statement usually at least a paragraph in length. For additional discussion and references see Eisenhart [35], Ku [36], Natrella [13], and Campion, et al.[37].

This purist approach does not seem practical. First, it is not amenable to large compilations


ALL CONCEIVABLE SOURCES OF INACCURACY
RANDOM UNCERTAINTIES
estimate, calculate a dispersion statistic for each
SYSTEMATIC UNCERTAINTIES
evaluate and assign a magnitude for each

(e.g., the quarterly EPA Environmental Radiation Data reports) of data from numerous sources. And second, it shifts the burden of evaluating the uncertainties to users. "Users now need, and will do so for many years to come, a single error value resulting from the combination of all the uncertainties. Indeed, a compromise leading to a single error value seems to be better than a perfect solution which in reality shifts the problem of combination of errors to the users"[34].

Several arguments can be advanced for favoring the standard deviation as a measure of the random uncertainty over higher confidence limits. It facilitates subsequent data handling since all weighting and uncertainty propagation is performed with the variances. A stronger argument is that the variance is the only statistic which is derived directly and unambiguously from the measurements. It is unbiased and distribution-free. Converting the measured standard deviation to some other confidence interval requires an assumption that the distribution is known. This equally applies to the use of the Student-t value. "Since an arbitrary multiple of a standard deviation(s) does not contain more information than s itself, the simplest and most reasonable choice of indicating the (random) uncertainty of an experimental result seems to me to go on stating its standard deviation, eventually completed by the number of measurements it is based on"[38].

The arguments for retaining the use of the standard deviation do not address the question of combining it with systematic uncertainties. If one agrees that the systematic uncertainties are to be expressed as estimated maximum limits (the semi-range), then some higher confidence interval for the random uncertainty part (e.g., 99.7% for $3s_x$ for a Normal distribution) provides an acceptable or reasonable level for diret combination with the systematic uncertainty. One can also invoke an argument for which confidence coefficient will be of greatest value to the user of the data. Returning to the original question posed in the example of Section III for a reported value of 15 ± 3 Bq (How certain is the user that the value is between 12 and 18 Bq?"), a high confidence coefficient may be the only unambiguous and unequivocal choice. How sophisticated is the user in ascertaining the meaning and correctly interpreting a 67% confidence interval? If the reported uncertainty is to be a statement of the "likely limits to the accuracy," then a high confidence interval may be the best choice.

Several acceptable models for propagating the systematic uncertainty components and combining them with the total random uncertainty may be considered. The two most commonly employed methods are:

A. Add linearly all components of the systematic uncertainty and add it to the random part. Since the systematic uncertainties (δ_j) are considered to be 99% or greater confidence intervals, it logically should be added to the total random uncertainty at a similar confidence coefficient. Using this model, the overall uncertainty for a reported value x is

$$t_\nu(P=99^+\%)s_x + \sum_j \delta_j \qquad (21)$$

where s_x is an overall standard deviation based on ν degrees of freedom and t_ν $(P=99^+\%)$ is the Student-t value corresponding to a 99% or greater confidence coefficient. This is the approach favored by metrology and standardizing laboratories. It probably overestimates the total uncertainty, but can be considered as an estimate of the maximum possible limit. For example, if you estimated that five contributions of about equal magnitude made up the systematic error, you would have to be very unlucky if all five were minus. Yet, if there was one dominant contributor, it might be a very valid approximation.

B. Add in quadrature all of the systematic uncertainty components, and either add it linearly to s_x,

$$s_x + \sqrt{\sum_j \delta_j^2} \quad , \qquad (22a)$$

or add it in quadrature to s_x,

$$\sqrt{s_x^2 + \sum_j \delta_j^2} \qquad (22b)$$

These are frequently considered (erroneously) to be overall 68% confidence intervals. They are probably the most widely employed approaches (if an attempt was made to assess systematic uncertainties at all).

Actually, without making assumptions about the distributions of the systematic uncertainties it is impossible to proceed except to arbitrarily select some method, such as those above. One of the simplest set of assumptions that can be made is that 1) the component systematic uncertainties are all independent, and 2) they are distributed such that all values within the estimated limits are equally likely (rectangular distribution). This approach, often termed the PTB approach[39], is gaining in popularity.

With the above two assumptions, the rectangular systematic uncertainty distributions can be folded together to obtain a combined probability distribution for which the variance may be computed. This may then be combined in quadrature with that for the random uncertainty. In effect, the assumed Normal distribution of the random uncertainty is convoluted with the combined systematic uncertainty distribution to obtain an overall distribution. With this, the overall uncertainty limits at a given confidence coefficient can be evaluated. For the case of a number of comparably-sized component systematic uncertainties, a very reasonable estimate of the confidence interval $\pm u_x$ for any confidence coefficient P is

$$u_x = \sqrt{[t_\nu(P)s_x]^2 + \frac{\zeta_N(P)}{3} \sum_j \delta_j^2} \quad (23)$$

where $t_\nu(P)$ and $\zeta_N(P)$ are the Student-t factor and the value of the variate in a Normal distribution, respectively, for the same confidence coefficient P (see Table 9).* For the special case when one of the δ_j's is much larger than the others, then

$$u_x = \sqrt{[t_\nu(P)s_x]^2 + \zeta_R(P) \sum_j \delta_j^2} \quad (24)$$

is a better approximation, where $\zeta_R(P)$ is the value of the variate in a rectangular distribution for a confidence coefficient P. For additional details see Wagner [39] and Williams, et al.[40]

Recommended Statement of Overall Uncertainty and Final Result. There is no one clearly superior method out of the range of approaches to reporting an overall uncertainty. Yet, the diversity of current practices and methods either recommended or required by governmental bodies, or used by those who report data, make it difficult if not impossible to combine or compare the data in a manner that would be useful for determining trends or possible necessary actions. There is, therefore, a great need for uniformity in the method used to report the uncertainties of environmental radiation data. In hope of achieving greater uniformity, the PTB approach, which was outlined above, is recommended. The detailed recommendations for the assessment and propagation of uncertainties which follow are given in this spirit. The recommended method requires that each reported measurement result include the value, the total random uncertainty expressed as the standard deviation, and a combined overall uncertainty. Examples illustrating the method are given in Ref. [1]. This recommended approach may not be best for all purposes. It is intended to be useful and practical without imposing unnecessary burdens on the time, money and personnel resources of laboratories. Adoption of this method may eventually demonstrate its most serious shortcomings and ultimately lead to better methods.

TABLE 9

P	$t_{\nu=\infty}$	ζ_N	ζ_R
50%	0.6745	0.6745	1
68.3%	1	1	1
95%	1.960	1.960	1
95.4%	2	2	1
99%	2.576	2.576	1
99.7%	3	3	1

Recommendations

III.1 Every reported measurement result (x) should include an estimate of its overall uncertainty (u_x) which is based on as nearly a complete an assessment as possible.

III.2 The uncertainty assessment should include every conceivable or likely source of inaccuracy in the result.

III.3 Every conceivable source of inaccuracy should be classified into one of two categories depending on how the uncertainty is estimated.

The random uncertainty contributions are estimated by a statistical analysis of replicate measurements. The random counting error contribution may be estimated from single measurements by making the Poisson assumption.

The systematic uncertainty contributions are estimated by less rigorous methods as described in the text.

Until combined for the measurement result, the individual uncertainties in both categories should be retained separately.

III.4 Each random uncertainty component should be estimated in terms of its standard deviation (s_i), or the standard error of the mean ($s_{\bar{x}}$) for independent multiple measurements.

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*S. R. Wagner [PTB-Mitteilungen 89, 83-89 (1979)] recently pointed out that the quadratic sum of confidence intervals [as in Eqs. (23) and (24)] is without theoretical basis. The overall uncertainty u_x for any confidence coefficient P is more properly obtained by

$$u_x = k_P \sqrt{s_x^2 + \frac{1}{3} \sum_j \delta_j^2}$$

where k_P is the standardized variate corresponding to P for the combined random and systematic uncertainty probability distribution.

III.5 The total random uncertainty (s_x) should be obtained by propagating the individual variances (s_i^2) for each random uncertainty component. This would include not only the Poisson counting error and random uncertainty derived from the particular measurement under concern, but also the random components from corrections, constants, calibration factors and any other measurements that make up the final result x. Many of these sources of inaccuracy are tabulated and discussed in Ref. [1]. These contributions may be combined by summing in quadrature or by the use of propagation of error formulae, such as Eq. (5) or those in Table 5. This overall random uncertainty may be represented by

$$s_x^2 = \sum_{i=1}^{p} \alpha_i \qquad (25)$$

which was given as Eq. (6) for p independent random uncertainty components.

III.6 Systematic uncertainties are considered to be independent and each is expected to be uniformly distributed over its range ($\pm\delta_j$). Each systematic component (δ_j) should be estimated in terms of the semi-range about the measurement result for the contributing source of inaccuracy [as in Eq. (15)].

III.7 The random and systematic uncertainties should be combined to form an overall uncertainty on the result x by

$$u_x = \sqrt{s_x^2 + \frac{1}{3} \sum_{j=1}^{q} \delta_j^2} \qquad (26)$$

where s_x is the standard deviation corresponding to the overall random uncertainty and δ_j is the magnitude of the estimated systematic uncertainty for each of the q systematic uncertainty components.

Alternatively, the overall uncertainty on the mean for averaged results should be given by

$$u_x = \sqrt{s_{\bar{x}}^2 + \frac{1}{3} \sum_{j=1}^{q} \delta_j^2} \qquad (27)$$

where $s_{\bar{x}}$ is the standard error of the mean [Eq. (3)]. Similarly, the overall uncertainty derived from p random uncertainty components and q systematic uncertainty components should be given by

$$u_x = \sqrt{\sum_{i=1}^{p} \alpha_i + \frac{1}{3} \sum_{j=1}^{q} \delta_j^2} \qquad (28)$$

For the special case if one of the systematic components (δ_1) is greater than one-third the sum of all the components, i.e.,

$$\delta_1 > 1/3 \sum_{j=1}^{q} \delta_j^2 ,$$

then the overall uncertainty should be given by

$$u_x = \sqrt{s_x^2 + \sum_{j=1}^{q} \delta_j^2} \qquad (29)$$

(or comparable equations analogous to Eqs. (27) and (28) which do not include the factor of 1/3.

III.8 Every reported measurement result x (or mean $\bar{x}$ for averages of results) should include a three-part requirement for the reporting of uncertainties:

(a) the value of the result x (or mean $\bar{x}$);

(b) the propagated total random uncertainty expressed as the standard deviation s_x (or standard error of the mean $s_{\bar{x}}$ for results based on multiple determinations of x or for averaged results of x); and

(c) the combined overall uncertainty u_x (or $u_{\bar{x}}$) as in Eqs. (26), (27), (28), or (29).

When short-hand expressions are necessary, the measurement result should be reported in the format

$x \pm s_x;\ u_x$.

For example, a result of $x=123\ \mathrm{Bq \cdot L^{-1}}$ with $s_x=15\ \mathrm{Bq \cdot L^{-1}}$ and $u_x=18\ \mathrm{Bq \cdot L^{-1}}$ should be reported in exponential notation as

$(1.23 \pm 0.15;\ 0.18)\ \mathrm{E{+}02\ Bq \cdot L^{-1}}$

III.9 Confidence intervals based on the overall uncertainty should not suggest a particular confidence coefficient. Rather, the two reported uncertainties may be referenced as:

> "The total random uncertainty is the propagated standard deviation (or standard error of the mean) of all sources of random uncertainty."

> "The overall uncertainty was propagated by adding in quadrature the total random uncertainty and one-third of the estimated upper limits of all conceivable sources of systematic uncertainty."

Confidence limits for a measurement result at a particular confidence coefficient cannot be obtaind by merely multiplying the uncertainty by arbitrary constants and adding and subtracting this value to and from the result. Determination of limits for higher confidence coefficients requires knowledge of the underlying population distribution, and knowledge of the number of measurements, degrees of freedom, or magnitude of the counts.

IV. DETECTION LIMITS

A myriad of vastly different expressions and definitions of "detection limits" are frequently encountered. Their meanings are often ambiguous, inconsistent and incorrectly interpreted. Some of these include "detection sensitivity," "minimum detectable activity (or level)," "lower limit of detection," and "background equivalent activity." Currie[14] commented on a number of such terms and addressed some of the problems and inconsistencies.

Pragmatically, a detection limit is useful as a criterion for experiment design, comparison and optimization purposes, such as in selecting among alternative measurement procedures. Additionally, detection limits may serve as guides which are set by regulatory bodies for establishing minimum acceptable detection capabilities for a given type of analysis. For the purposes of this report, the intent of detection limit calculations is to satisfy both of the uses. It must be emphasized that any calculation of a detection limit is at best only an estimate. Their use is "limited to that of serving as guideposts only, and not as absolute levels of activity that can or cannot be detected by a counting system."[14]

Much of the existing confusion with detection limits for environmental ionizing radiation measurements arises from not only the large number of different expressions that are in use, but also from incorrect interpretations and misapplications of some of the original definitions. In order to satisfy both of the above-mentioned purposes, two distinctly different concepts are required.

The first is an estimated detection limit that is related to the characteristics of the counting instrument. It is not dependent on other factors involved in the measurement method or on the sample characteristics. It is a lower limit in the true sense of the word. Because of its current wide usage, the recommended term is the ESTIMATED LOWER LIMIT OF DETECTION (LLD).

The second concept is that most useful for regulatory purposes. It corresponds to a level of activity concentration that is practically achievable with a given instrument, method and type of sample. It depends not only on the instrument characteristics, but also on many other specific factors involved in the measurement process, as well as the characteristics of the sample being measured. As such, it is not a limit at all, but only an estimated level achievable under a given set of practical conditions. The recommended expression for this concept is the ESTIMATED MINIMUM DETECTABLE CONCENTRATION (MDC).

It is recommended that only these two expressions be employed for all environmental radiation measurement detection limits. Both the LLD and MDC concepts can be based on a uniform consistent methodology. The use of this methodology with only these two expressions should help alleviate and avoid much of the existing ambiguity and misapplications. Both the LLD and MDC concepts will be considered in turn. If the word "estimated" is emphasized and continually used in reporting a LLD and MDC, then their limited nature should be more apparent, and hopefully avoid the implication of an absolute significance in their numerical values.

The Estimated Lower Limit of Detection (LLD)

THE LLD may be defined on the basis of statistical hypothesis testing for the presence of activity. This approach is common to both that of Pasternack and coauthors[42,43], and Currie[41]. Procedures for calculating a LLD based on this approach have also been described in the EML Procedures Manual[44], the EPA quality control program report[24], and the NCRP Handbook of Radioactivity Measurements Procedures[14].

Pasternack and Harley[43] defined the LLD as "the smallest amount of sample activity that will yield a net count for which there is a confidence at a predetermined level that activity is present."[44] In theory, this approach for calculating a LLD requires the number of counts to be sufficient for the Poisson distribution to approach the Normal distribution so that Gaussian statistics can be applied. It has been noted, however, that in practice "the approximation is good down to a few total counts."[44] The LLD is an "*a priori* ESTIMATE of the detection capabilities of a given measurement process."[41] It is based on the premise that from a knowledge of the background count and measurement system parameters (i.e., detection efficiency), an *a priori* (before the fact) limit can be established for a particular measurement. This limit does not depend on the sample activity, but rather on the detection capability of the measurement process itself. It is important in the application of the LLD to make the distinction between it and other limits that are directly applicable to the net sample activity. The latter are applied as a posteriori limits (after the fact) and can be determined only after the sample has been counted.

The LLD is derived from the approximation

$$\text{LLD} = K\,(k_\alpha s_0 + k_\beta s_D) \qquad (30)$$

where

K	is the proportionality constant relating the detector response (counts) to the activity, such as, $K=1/\epsilon$ where ϵ is an overall detection efficiency, or $K=1/I_\gamma \epsilon_\gamma$ where I_γ is the gamma ray-emission probability per decay and ϵ_γ the detection efficiency for the gamma ray.
k_α	and k_β are the upper percentiles of the standardized normal variate corresponding to the preselected risk for concluding falsely that activity is present (α) and the predetermined degree of confidence for detecting its presence ($1-\beta$)
s_0	is the estimated standard deviation of the net sample count (N_n) when the limiting mean of N_n equals zero
s_D	is the estimated standard deviation of the net sample count (N_n) when the limiting mean of N_n equals the LLD.

The basis for this approximation for the LLD is illustrated in Figure 3. Additional details and discussion may be obtained in References[41], [42] and [43]. In statistical hypothesis testing, α and β are the probabilities for what are frequently referred to as Type I (false detection) and Type II (false non-detection) errors, respectively. Values for k_α and k_β corresponding to the risks for false detection (α) and non-detection (β) can be found in most statistical texts. As stated before, this assumes that the random uncertainties are normally distributed. In general, both α and β should be reasonably small in order to provide a high degree of confidence that neither type of error will be made. If $\alpha = \beta = 0.5$ (i.e., a 50% risk for each type of error), then the LLD would always be zero. In this case, activity detection near the LLD will be wrong 50% of the time, and "the experiment could be performed equally well by the flipping of a coin."[41] Conversely, if α and β are set very small (say $\alpha = \beta = 0.001$), then one would rarely be incorrect. At the same time, however, one would seldom attribute significance to anything but very large activity measurements. A convenient compromise and most common practice is to set both risks equal, and to accept a 5% chance of incorrectly detecting activity when it is absent ($\alpha = 0.05$) and a 95% confidence that activity will be detected when it is present ($1-\beta = 0.95$). Then

$$k = k_\alpha = k_\beta = 1.645 \quad (\alpha = \beta = 0.05), \qquad (31)$$

which is recommended for use in all environmental radiation LLDs. It is incorrect to refer to this as a 5% confidence level. First, the LLD cannot be characterized by a single confidence level; and second, its use can lead to confusion with the confidence level for an a posteriori decision on the presence of activity after the measurement is made. Preferred language is THE ESTIMATED LLD FOR 5% RISKS OF FALSE DETECTION AND FALSE NON-DETECTION.

Using the recommended approximation of Eq. (30) and the convention of Eq. (31), several typical and specific applications can be developed.

Consider measurement processes in which the net activity is derived by subtracting a background from a gross activity measurement. The standard deviation of the net activity is

$$s_n = \sqrt{s_g^2 + s_b^2} \qquad (32)$$

where s_g and s_b are the standard deviations of the gross activity and background, respectively. If the gross activity and background counts are nearly equal (which is a reasonable approximation near the LLD), then Eq. (32) reduces to

$$s_n = \sqrt{2}\ s_b \qquad (33)$$

Further, if one assumes that s_n over the small range of net activity from zero to the LLD is

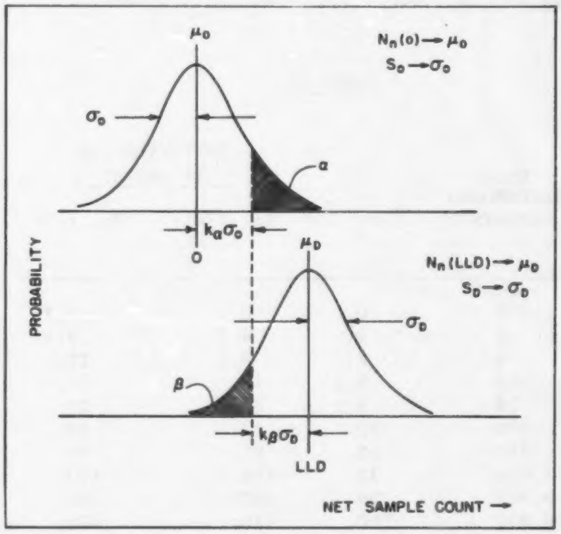

Figure 3. Probability distributions of the net sample count (N_n) at zero and at the LLD illustrating the relations $k_\alpha s_o$ and $k_\beta s_D$.

approximately constant, i.e., $s_n = s_0 = s_D$, then from Eqs. (30) and (33)†

$$\begin{aligned} LLD &= Kk2\sqrt{2}\ s_b \qquad (34) \\ &= 4.65\ K\ s_b \ . \end{aligned}$$

Alternatively, if one does not make the above assumption ($s_0 \neq s_D$), Currie [41] has shown that the expression for the LLD becomes

$$\begin{aligned} LLD &= K\ (k^2 + 2\sqrt{2}\ \ ks_b) \qquad (35) \\ &+ K\ (2.71 + 4.65\ s_b) \ . \end{aligned}$$

Except at extremely small counts, the difference in the two calculations is trivial (see Table 10). For a Poisson distribution, s_n is not as independent of the activity level and Eq. (35) may be a better approximation. In most cases, both calculations will be comparable. When they are not (e.g., extremely small background counts), Eq. (35) is recommended.

In many applications, the measurement procedure would frequently consist of a paired sequential observation of the gross and background counts. One could envisage obtaining a single background value which is not exactly equal to the known long-term average background. This single measurement would be used as a check, and perhaps to continually update the average. To calculate a new LLD from a single observation is without merit. It would ultimately lead to a LLD for each and every background measurement. This approach would defeat the spirit of the LLD concept which is to provide an A PRIORI ESTIMATE or a guidepost of the detection capability of the instrument. Similarly, the quantities contained within the proportionality constant K, such as the detection efficiency, should be average values for the instrument. If the values vary substantially from measurement to measurement, or if they abruptly change, then this would suggest that there is a serious instrument or procedural problem. This erratic behavior may be due to an instrument malfunction, or may be an indication of poor laboratory practice. Under any circumstance, it demonstrates the existence of a problem, and should serve as a stimulant to ascertain the cause of the problem (see "blunders," in Part III). If the measurement process or procedure is modified, or if substantive changes in the background or in any of the parameters comprising the proportionality constant K occur, then the LLD should be recalculated.

TABLE 10

TOTAL BACKGROUND COUNTS	s_b	ESTIMATED LLD (K units) Eq. (34)	Eq. (35)
0	0	0	2.7
1	1.	4.7	7.4
4	2.	9.3	12.
10	3.2	15.	17.
35	5.9	28.	30.
100	10.	47.	49.
350	19.	87.	90.
1,000	32.	150.	150.
3,500	59.	280.	280.
10,000	100.	470.	470.

The Estimated Minimum Detectable Concentration (MDC)

The MDC is a level (not a limit) of activity concentration which is practically achievable by an overall measurement method. As distinguished from the LLD, the MDC considers not only the instrument characteristics (background and efficiency), but all other factors and conditions which influence the measurement. It is an *a priori* estimate of the activity concentration that can be practically achieved under a specified set of typical measurement conditions. These include the sample size, counting time, self-absorption and decay corrections, chemical yield and any other factors that comprise the activity concentration determination. It cannot serve as a detection limit *per se*, for any change in measurement conditions or factors will influence the value of the MDC. Its use is limited to establishing, for regulatory purposes, that some minimum overall measurement conditions are met. Any of several factors, such as sample size or counting time, could be varied to satisfy these regulatory values.

Expressions for the MDC can be derived analogously to those for the LLD using the approximation of Eq. (30) and convention of Eq. (31). The results are

$$MDC = 4.65\ K^*\ s_b \qquad (36)$$

or

$$MDC = K^*(2.71 + 4.65\ s_b) \qquad (37)$$

which are analogous to Equations (34) and (35) for the LLD. The proportionality constant K*, in this case, relates the detector response (counts) to the activity concentration in a sample for a given set of measurement conditions. It may, for example, consist of

$$K^* = \frac{1}{YVTS\ \varepsilon\exp(-\lambda t)} \qquad (38)$$

where Y is the fractional yield for the radiochemical separation;

V is the sample size;

T is the counting time interval;

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†A value of 4.66 has also been frequently used for the quantity $2\sqrt{2}\ k$ [Cf. Ref. 44]. The difference is merely one of rounding.

S is the self-absorption correction factor;

ε is the detection or counting efficiency;

$\exp(-\lambda t)$ is the correction for radioactive decay between sample collection and counting (time interval, t);

λ is the decay constant for the particular radionuclide with half-life $T_{1/2} = \ln 2/\lambda$.

As discussed previously when considering the K for the LLD, all of the factors contained within the proportionality constant K* for the MDC should be typical or average values for the instrument and measurement procedure.

Misapplication of the LLD or MDC for A Posteriori Decisions

As stated earlier, the LLD is an a priori estimate dependent on only the instrument background and detection efficiency, and the MDC is an a priori estimate for a given type of analysis or measurement process under specified typical conditions. They are not a posteriori decision limits for every measurement. They need not, and should not, therefore, be calculated for each individual measurement. The practice of comparing a unique computed LLD or MDC for each measurement against the measurement result should be avoided. This has sometimes been employed to determine the "significance" of the result for reporting purposes.

If results below a particular computed LLD or MDC are rejected or excluded from data reports, serious errors and distortion in long-term trends could result. Consider the hypothetical situation illustrated in Figure 4. The background is represented by the probability distribution with the mean μ_b and standard deviation σ_b. Similarly, a gross count is given by the distribution with mean μ_g and standard deviation σ_g. Thus the net count, obtained by subtracting the background from the gross count, is the probability distribution with mean $\mu_n = (\mu_g - \mu_b)$ and variance $\sigma_n^2 = (\sigma_g^2 + \sigma_b^2)$. This net count distribution can be compared, as shown, to the estimated LLD calculated with the standard deviation of the background (σ_g) using Eq. (35). In this case, the true or limiting mean of the net count, and a substantial fraction of the distribution are below the computed LLD. A resultant net count (N_n) from a typical individual paired observation of background and gross counts (N_b, N_g), which are both well within $\pm\sigma$, is illustrated. If this value and many others less than the LLD are not reported, then the distribution of the reported values would grossly distort the true situation given by μ_n and σ_n for the population. This point is demonstrated further in the data of Table 11. In this example, twenty-five net count (N_n) measurement results from a population with a mean of 20 were obtained from paired observations of background (N_b) and gross counts (N_g). The average background of 16 counts was used to estimate the LLD:

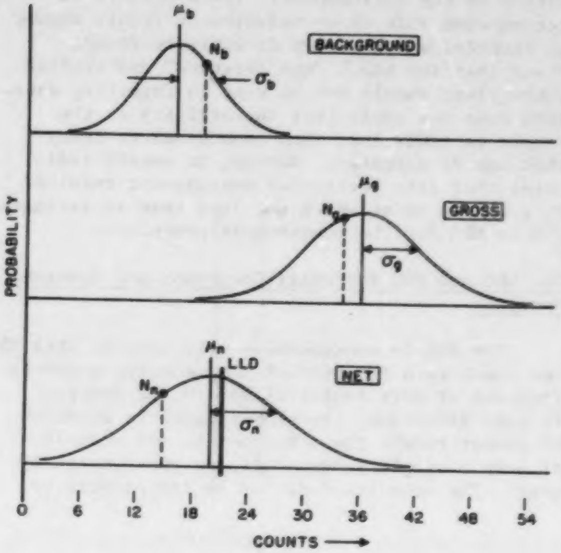

Figure 4. Illustration of the LLD and its relation to the underlying population distributions in a hypothetical measurement situation. See text for details.

$$\text{LLD} = 2.71 + 4.65\sqrt{16}$$

$$= 21.3 \text{ counts} \quad \text{[from Eq. (35)]}$$

or

$$\text{LLD} = 4.65\sqrt{16}$$

$$= 18.6 \text{ counts} \quad \text{[from Eq. (34)].}$$

The last two columns in the table contain the tabulated results when values less than 21.3 and 18.6 counts are reported as "less than the LLD" (<LLD). In the first case, only 8 of the 25 measured results would be specified. How does one average this tabulation? The average of the 8 specified values is 25.4 counts, which may be contrasted to the population mean of 20 counts. If the other 17 "<LLD" values are taken as being equal to the LLD* (21.3 counts), the average of the 25 values becomes 22.6 counts. Even if one invokes the less restrictive LLD of 18.6 counts, 9 of the 25 measured values are "<LLD."

This distortion of values near the LLD or MDC will always result in a positive bias when one attempts to make realistic estimates over a period of time. The implications can be serious. When making measurements near background levels, one can expect to frequently obtain values that are less than the estimated LLD or MDC. If these values are not recorded and used in making average estimates, then these estimates are always going to be greater than the "true" representation of the environment. Therefore, it is recommended that every measurement result should be recorded and reported directly as found. "Less than the LLD," "not detected" and similar expressions should not be used in reporting data. This does not imply that the activity in the sample is truly less than some absolute level that can be detected. Rather, it merely indicates that this particular measurement resulted in a single value which was less than an estimated LLD or MDC for the measurement procedure.

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* This conservative approach may be the most likely treatment when the tabulated results are ultimately used to make dose assessments.

The LLD and MDC for Multi-Component and Spectral Analyses

The MDC is conceptually more complex when the net count is a function of the detector response from two or more radionuclides in the sample. In this situation, the proportionality constant K* cannot relate the net count to the activity of just a single radionuclide as was previously done. The simplest case can be represented by

$$N_n = A_1 C_1 \epsilon_1 + A_2 C_2 \epsilon_2 \qquad (39)$$

where A_1 and A_2 refer to the activities of two different radionuclides, ϵ_1 and ϵ_2 are the respective detection efficiencies, and C_1 and C_2 are the respective constants which include chemical yields, absorption corrections, decay factors, etc. Then, the LLD for A_1 and A_2 are just given by

$$\begin{aligned} LLD(A_1) &= K_1(2.71 + 4.65 s_b) \\ LLD(A_2) &= K_2(2.71 + 4.65 s_b) \end{aligned} \qquad (40)$$

where $K_1 = 1/\epsilon_1$ and $K_2 = 1/\epsilon_2$. Obviously, this interpretation results in an LLD for A_1 when A_2 is absent. And conversely, the LLD for A_2 is independent of the amount of A_1. For purposes of the LLD calculation then, Equation (39) in effect reverts to either $N_n = A_1 C_1 \epsilon_1$ (with A_2 absent) or $N_n = A_2 C_2 \epsilon_2$ (with A_1 absent). For many procedures, such as the determination of ^{89}Sr and ^{90}Sr, with typical samples, this approach has been subject to the criticism that

TABLE 11

N_b	N_g	N_n	s_n	Distorted N_n Reported Values for LLD=21.3	 for LLD=18.6
20	38	18	7.6	<LLD	<LLD
15	36	21	7.1	<LLD	21
18	34	16	7.2	<LLD	<LLD
21	27	6	6.9	<LLD	<LLD
16	36	20	7.2	<LLD	20
17	41	24	7.6	24	24
14	33	19	6.9	<LLD	19
16	44	28	7.7	28	28
17	35	18	7.2	<LLD	<LLD
19	38	19	7.5	<LLD	19
12	32	20	6.6	<LLD	20
15	36	21	7.1	<LLD	21
16	39	23	7.4	23	23
18	34	16	7.2	<LLD	<LLD
23	43	20	8.1	<LLD	20
14	31	17	6.7	<LLD	<LLD
11	28	17	6.2	<LLD	<LLD
16	35	19	7.1	<LLD	19
10	40	30	7.1	30	30
15	37	22	7.2	22	22
22	38	16	7.7	<LLD	<LLD
16	30	14	6.8	<LLD	<LLD
13	37	24	7.1	24	24
17	44	27	7.8	27	27
9	34	25	6.6	25	25
16	36.	20.		(22.6) 25.4	(21.1) 22.6

All values in counts.

it does not reflect realistic detection capabilities. It is sometimes argued that the LLD must consider that any net count N_n results from contributions from both ^{89}Sr and ^{90}Sr. This argument is another misapplication of the LLD concept. If it is accepted, then the LLD would no longer be a limit and would be dependent on something other than the instrument background and efficiency characteristics.

The MDC, however, is intended to serve as a practical level that is achievable under a given set of specified measurement conditions, and must consider the effect of multi-components in the sample. Referring again to the case of Equation (39), the MDC for A_1 can be written

$$MDC(A_1) = K_1{*}2ks_1 \qquad (41)$$

where $k = k_\alpha = k_\beta = 1.645$, and s_1 is the estimated standard deviation of the net sample count corresponding to A_1 over the range of net activities from $A_1 = 0$ to $A_1 =$ MDC, i.e. $s_1 = s_o(1) = s_D(1)$ [refer to Eq. (30)]. Since the net sample count corresponding to A_1 is given by

$$N_1 = N_{1+2+b} - N_2 - N_b \quad ,$$

the estimated standard deviation s_1 is

$$s_1 = \sqrt{s^2{}_{1+2+b} + s^2{}_2 + s^2{}_b} \quad ,$$

and, with $s^2{}_{1+2+b} = s^2{}_{1+b} + s^2{}_2 \quad ,$

$$s_1 = \sqrt{s^2{}_{1+b} + 2s^2{}_2 + s^2{}_b} \quad .$$

If the gross counts N_{1+b} and background N_b are approximately equal (which is a reasonable assumption near the MDC), then s_1 reduces to

$$s_1 = \sqrt{2s^2{}_b + 2s^2{}_2}$$

$$= \sqrt{2} \quad s_b \sqrt{1 + \frac{s^2{}_2}{s^2{}_b}}$$

Making a Poisson assumption, $s^2{}_2$ becomes

$$s^2{}_2 = \frac{N_2}{T^2} = \frac{A_2C_2\varepsilon_2}{T^2} \quad ,$$

where C_2 and ε_2 were given in Eq. (39) and T is the count time. Hence,

$$s_1 = \sqrt{2} \quad s_b \sqrt{1 + \frac{A_2C_2\varepsilon_2}{s_b{}^2T^2}} \quad ,$$

and substitution into Eq. (41) yields

$$MDC(A_1 = K_1{*}2\sqrt{2} \quad k \quad s_b \sqrt{1 + \frac{s_2{}^2}{s_b{}^2}}$$

$$= K_1{*}(4.65s_b) \quad \sqrt{1 + \frac{A_2C_2\varepsilon_2}{s_b{}^2T^2}}. \qquad (42)$$

Analogously to Eq. (37), the MDC for A_1 may alternatively be given by

$$MDC(A_1) = K_1{*}\left[2.71 + 4.65s_b \sqrt{1 + s^2{}_2/s^2{}_b}\right].$$
$$= K_1{*}\left\{2.71 + 4.65s_b \sqrt{1 + \frac{A_2C_2\varepsilon_2}{s_b{}^2T^2}}\right\}. \qquad (43)$$

The factor $K_1{*}$ is, by definition, given by

$$K_1{*} = \frac{A_1}{N_n} = \frac{1}{C_1\varepsilon_1 + \left(\frac{A_2}{A_1}\right)C_2\varepsilon_2} \quad , \qquad (44)$$

and is dependent on the relative amount of activity A_2 since the net count is apportioned between that due to A_1 and that due to A_2.

One is therefore confronted with a paradox. The MDC should be an a priori estimate, but its determination requires a posteriori knowledge of the amounts of activity in the sample. This dichotomy can be overcome by calculating the MDC for typical sample conditions. This is subject to criticism that some samples may vary substantially from the typical, and that the MDC may then be in considerable error. Without denying this argument, there are two reasons why the effects from such errors are unimportant. First, the MDC is only to be an ESTIMATE; and second, all measurement results should be reported without a comparison to the MDC. As a result, there is no great need for knowing some absolute detection level for every measurement.

The determination of a LLD and MDC for activity measurements by gamma-ray spectrometry is a good example of the above described situation. It is complicated in that the background count rate for the same radionuclide may vary from sample to sample. This is due to the fact that the background is usually the sum of two separate sources of gamma radiation. First, there is the system background radiation for a blank, corresponding to the sample to be measured, as discussed previously. Second, there is Compton-scattered radiation from other higher energy gamma rays in the sample. Thus, it is readily seen that the measurement of blank backgrounds has meaning only for very specific situations, e.g., when only one radionuclide is present in the sample, or when the radionuclide of interest emits the highest energy gamma ray.

It then follows that the LLD, which is independent of sample conditions, is a function of only the instrument performance (as contained within K) and the uncertainty in this blank background, i.e.

$$LLD = f(K, s_{\substack{blank\\bkgnd}}) \qquad (45)$$

Blank backgrounds are also useful for evaluating the adequacy of shielding and system performance. A large deviation in blank background values may indicate instrument malfunction.

For environmental samples one can assume that almost always two or more gamma-emitting radionuclides will be present in any given sample, thus a more realistic background must be determined for calculating a MDC. This sample background will depend upon the relative amounts of other radionuclides that are present in the sample and the energy of each of their gamma rays. One can then represent the MDC as a function of K* and the uncertainty in this sample background, i.e.

$$MDC = f(K^*, s_{\substack{sample\\bkgnd}}) \qquad (46)$$

Pasternack and Harley [43], for a number of typical counting situations, considered the influence of other radionuclides on the detection limit in mock multi-component samples. Their experimental comparisons were made with large NaI(Tl) detectors. This was extended by Wrenn, et al.[45] for the effect of the presence of natural radionuclides on the detection limits of man-made radionuclides in environmental samples. They also made comparisons to Ge(Li) spectrometry. The general problem of detecting small photopeaks in Ge(Li) spectra was also addressed by Head[46]. Fisenne, et al.[47] applied the Pasternack and Harley[43] approach to multi-component alpha spectrometry which has pulse-height distribution data that is very similar to that of gamma spectrometry. In all cases, the MDC for a particular radionuclide was shown to be dependent on the composition of the sample. It depends upon the number, quantity, and spectral characteristics of the other radionuclides in the sample.

Therefore, to satisfy the condition that the MDC be an *a priori* estimate, it is recommended that it be calculated for each radionuclide from typical spectrum backgrounds for each type of sample.

Examples of these more complex MDC calculations such as for multi-component and spectral analyses can be found in Ref. [1].

Interpretations and Restrictions

In summary, the major concepts underlying the Lower Limit of Detection (LLD) and Minimum Detectable Concentration (MDC) are:

1. The LLD should be viewed as an *a priori* estimate or guidepost of the detection capability for an instrument. Its value is dependent upon only the detection instrument characteristics (e.g., the efficiency) and the uncertainty in the instrument's background.

2. The MDC should be viewed as an *a priori* estimate or guidepost of the level of activity concentration that is practically achievable by a specific given instrument, measurement method and type of sample. Its value is dependent upon the characteristics and conditions of the overall measurement system (instrument and method) and on the sample characteristics.

The LLD and MDC are only estimates, and not absolute levels of activity or activity concentration that can or cannot be detected. Similarly, they are not intended to be *a posteriori* criteria for the presence or absence of activity.

The practical significance of the estimated LLD and MDC are only to serve as guideposts or criteria for experiment design, comparison and optimization purposes, and to serve, for regulatory purposes, as approximate guidelines of minimally acceptable levels that can be practically achieved. As such, all measurement results should be reported directly as obtained, and the estimated LLD or MDC should not be employed to exclude some results from reports. Similarly, the practice of calculating a new LLD or MDC value for every measurement defeats the spirit of the concepts which are to provide *a priori* estimates. *A posteriori* calculations contain no additional information, and are neither technically or economically justifiable.

The above interpretations place some important restrictions on the use of the LLD or MDC, particularly with respect to satisfying regulatory specifications. The most important restriction is that it is unreasonable for a regulator to establish absolute values for the MDC or LLD for various combinations of radionuclide and type of sample media, and then expect compliance 100% of the time in all situations. Even ideally the MDC and LLD, by convention, involve 5% risks of false-detection and false non-detection.

A further restriction arises from the fact that the MDC for a radionuclide may vary from sample to sample depending on the characteristics of the sample. For example, the MDC for a radionuclide assayed by gamma-ray spectrometry depends upon the number, quantity, and spectral characteristics of other radionuclides which may be present in the sample. It must therefore be recognized that an MDC established for one specific set of conditions may not be applicable for all other conditions.

Detection capabilities, notably those specified by the Nuclear Regulatory Commission, are stated to be "state-of-the-art for routine environmental measurement"[48]. If these state-of-the-art values are established for one set of assumptions (instrument, procedures and sample variables), then the MDC values should not be expected to be technically achievable unless the assumptions, particularly typical sample composition, are still valid. Although NRC documents reflect this view[48,49], a number of licensees have reported cases where inspectors have interpreted the MDC as an absolute level, and have tested licensees for specification compliance with simulated spiked samples. If an MDC contained within a licensee's Technical Specifications was determined with blanks or typical samples, then there is no reason to expect the same value to be applicable for atypical samples of dissimilar composition.

The frequent use of an MDC or LLD as a criterion for excluding some results from data reports must not continue. The resulting positive biasing effects of this practice were discussed previously. As a result, it is recommended that all measurement results be reported directly as found; and that "less than MDC" and similar terms never be used.

For some measurements, the reporting of all results will not present a problem. Others, like automated gamma-ray-spectrometer systems, can, however, present a practical problem. Some computer-coupled systems which routinely test for upwards of a hundred or so radionuclides in a system library would require a data report consisting of a value for every radionuclide in the library. Obviously, such an approach is not reasonable. The current practice of using MDC values to decide which results from the long list will be reported is not the solution. What is needed is a practical approach that avoids the problems inherent in using a preselected exclusion criterion, but at the same time is reasonable. This approach requires that efforts be made to reflect on the purpose of the measurements. Measurement of a hundred different radionuclides in a surveillance or monitoring program is neither reasonable or justifiable. Fewer reliable measurement results are much better than many questionable results. What is needed are more good measurements whose results can be viewed with confidence, not more measurements per se. The criteria for what should be measured (and hence reported) should be based upon what is actually needed for the purpose of environmental radioactivity monitoring [50] and upon the dosimetric significance of the radionuclides. Attempts to measure everything that is technically achievable do not serve anyone (not the laboratories or the public). Laboratories, as well as regulators, must begin to recognize this. An approach which is more reasonable and justifiable in terms of the dosimetry and purposes of the monitoring must be taken when designing measurement and data reporting programs.

A practical approach to this problem may be for laboratories and regulators to preselect only those measurements which are reasonable and justifiable in terms of the dosimetry and purposes of the monitoring program. The effect of this preselection could be evaluated and its magnitude incorporated as a systematic uncertainty component in the assessment and propagation of an overall uncertainty (see Part III). In gamma-ray spectrometry with automated systems, for example, the magnitude of this systematic uncertainty could be evaluated by analyzing a test spectrum first without any preselection criteria, and then with a limited system library containing only the preselected radionuclides. The difference between the two results could be used as an estimate of the additional systematic uncertainty. This uncertainty component could be evaluated for each preselected radionuclide of interest using test spectra containing a full range of radionuclides found in typical samples. This practical approach may be a reasonable compromise.

Recommendations

IV.1 Only two expressions for detection limits, based on a uniform consistent methodology, should be employed. The recommended terms are the ESTIMATED LOWER LIMIT OF DETECTION (abbreviated LLD) and the ESTIMATED MINIMUM DETECTABLE CONCENTRATION (MDC).

IV.2 The practical significance of the estimated LLD and MDC are only to serve as guideposts or criteria for experiment design, comparison and optimization purposes, and to serve, for regulatory purposes, as approximate guidelines of minimally acceptable detection capabilities.

IV.3 The LLD should be viewed as an a priori estimate or guidepost of detection capability, and not as absolute levels of activity that can or cannot be detected. It is not intended to be an a posteriori criterion for the presence of activity.

IV.4 The MDC should be viewed as an a priori estimate or guidepost of the capability for detecting an activity concentration by a given measurement system, procedure and type of sample, and not as absolute activity concentrations that can or cannot be detected.

IV.5 The estimated LLD or MDC should be based on the approximation of Eq. (30) which is an approach derived from statistical hypothesis testing.

IV.6 The estimated LLD or MDC should be calculated, using the convention of Eq. (31), for "5% risks of false detection and false non-detection."

IV.7 The estimated LLD should be calculated from Eq. (34), (35), (40), (45) or comparable equations which are derived from the approximation of Eq. (30) and convention of Eq. (31).

IV.8 The estimated MDC should be calculated from Eq. (36), (37), (42), (43), (46), or comparable equations which are derivable from the approximation of Eq. (30) and convention of Eq. (31).

IV.9 The estimated LLD should be expressed in units of activity and should include only the instrument parameter which relates the detector response (counts) to activity. This normally would be only the detection efficiency or calibration factor for the instrument, and would not include other parameters such as the sample size, chemical yield, decay scheme parameters, absorption and attenuation corrections, decay factors, etc.

IV.10 The estimated MDC should be expressed as activity per unit mass or activity per unit volume, and its calculation would include all parameters which relate the detector response (counts) to the activity concentration in a given type of sample. These may include detection efficiencies, chemical yields, absorption and attenuation corrections, decay scheme parameters, decay factors, etc.

IV.11 The estimated LLD should be calculated using average blank backgrounds and efficiencies for the instrument; the estimated MDC should be calculated using average sample backgrounds and parameters for typical samples.

IV.12 The estimated LLD for a given instrument should be calculated for each radionuclide of interest, but it is independent of the sample characteristics; in contradistinction, the estimated MDC for a given procedure should be calculated for each radionuclide for each type of sample.

IV.13 To avoid possible positive biases in long-term data trends, all measurement results should be reported directly as obtained. "Less than LLD," "less than MDC," "not detected" and similar expressions should not be reported. Similarly, the LLD or MDC should not be used as a decision criterion for excluding some results from data reports.

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STATISTICAL METHODS FOR ENVIRONMENTAL RADIATION DATA INTERPRETATION

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The interpretation of environmental radiation data encompasses those activities and operations used to draw conclusions from measurements. In general, these conclusions will extend considerably beyond the collected data to the environmental compartments which the samples or measurements were intended to represent. This chapter summarizes the results of an evaluation of alternative statistical methods for data treatment and interpretation. Following a brief introduction, major Areas of Concern are discussed. Areas addressed are Experimental Design, Sampling Representativeness and Data Analysis. Recommended methods were chosen to provide the best possible input into dose evaluation procedures. In addition to containing recommendations for meeting minimum requirements in the Area of Concern, several particularly troublesome topics are discussed. Among these are establishing a reliable baseline, quantifying variables in the sampling equation and handling less-than-lower-level-of-detection data.

(Accuracy; baseline study; critical pathway analysis; data analysis; data interpretation; distribution analysis; dose assessment; environmental compartments; experimental design; homogeneity; lower limit of detection [LLD]; precision; probability plots; radiation; representativeness; sampling; statistics; surveillance objectives; variability)

Statement of the Problem

The general purpose of environmental radiation surveillance in the vicinity of any nuclear installation is to obtain information essential to assessing and controlling the exposure of the neighboring population to radiation and/or radioactive materials. Various components of the nuclear community supplement this purpose with secondary purposes in different ways. These alternative statements of objectives are discussed elsewhere in this document.

The necessity of adjusting environmental surveillance techniques to meet selected ones of these established objectives is a widely recognized, yet seldom followed, principle. Often a program is planned to meet several objectives, but without explicitly stating the rationale for any of these several objectives so that compatible data collection, treatment and interpretation techniques can be selected.

Recently, a variety of data handling techniques have come into common use. With the large number of techniques presently in use, it is nearly impossible to compare even similar data at different sites. Both the regulatory agencies and the public have deemed comparability of results to be desirable and hence the techniques suggested in this chapter have been adopted to help achieve that end.

The marked increase of public and regulatory interest in radiological environmental surveillance in recent years and the continuing decline in the environmental concentrations of most radionuclides make the appropriate and as-rigorous-as-possible data collection, treatment and interpretation techniques mandatory. Areas of concern in environmental surveillance which are affected by these changing requirements are (1) experimental design, (2) sampling, and (3) data analysis.

Two problem issues commonly encountered in the interpretation and reporting of environmental data are the treatment of "less-than-minimum-detection-limit" values, and the determination of contributions to the environment by a nuclear facility. Routine environmental surveillance data are best interpreted by treating the data as groups (not as individual datum) and plotting the groups on probability paper of some kind. Because the resulting distributions are presented graphically, the median, geometric standard deviation (on log-probability paper) or the mean and standard deviation (on linear-probability paper) can be readily determined visually. Contributions from operating plants and expected upper limits can also be identified.

The advantage of handling environmental surveillance data as distributions instead of individual datum points and graphically instead of numerically is that these distribution plots yield, with the same or less effort, average values and standard deviations that are the same as those obtained by numerical methods; quickly show whether the distribution choice was correct (as between Gaussian versus log-normal); or, whether the data belong to two statistical groups.

Groups of data including 10 to 100 items, the range of group sizes most common in environmental programs, can be handled efficiently by graphical methods. For example, weekly or monthly data may be grouped for interpretation. Sampling sites are generally limited to less than 100 in number. These graphical methods are equally useful for larger groups of data, but manual treatment becomes tedious, particularly for routine applications.

In this chapter the mechanics and applicability of the recommended data handling and interpretation techniques are detailed for each of the three areas of concern.

Areas of Concern

Experimental Design

Required Sensitivity. Evaluation of population doses from the "as low as practicable"* viewpoint has created pressure for increasingly sensitive radiation measurement and evaluation techniques. As a result, nearly all DOE sites, except for those with high energy machine radiations near site boundaries, currently report[3] maximum individual whole-body doses of less than one mrem per year for comparison with a standard[4] of 500 mrem per year. Supporting such dose estimates is the availability at most DOE and commercial laboratories of radioanalytical detection levels for the more common analyses, using practicable sample size and counting times, equivalent** to annual organ doses of less than 5 mrem (for most analyses less than 1 mrem). Detection levels of this magnitude for direct measurement of incremental external radiation in the environs are not readily available because of the comparatively large variability of natural radiation levels.

Attempts to calculate "health effects" in a large population exposed to miniscule doses, as well as the increased attention being paid by regulatory agencies and public interest groups to radiation levels far below the previously accepted standards, reinforce the desirability of achieving such dose discrimination levels when technology permits. This will become even more important within the next few years as power reactors and other non-DOE nuclear facilities governed by NRC licensing requirements begin to operate at locations sufficiently close to DOE facilities to have potentially overlapping environmental impacts. A few definitions are required before the details of this subject can be discussed.

Sensitivity Definitions. Confusion and noncomparability of reported data have resulted both from differing terminology for the measure of analytical sensitivity and from differing mathematical definitions. Frequently, as in DOE Manual Chapter 0513[6] and the EPA/ORP Environmental Radioactivity Surveillance Guide[5], "Minimum Detection Limit" or a similar term has been used without definition.

The Minimum Detectable Concentration, Minimum Detection Limit or Minimum Detectable Level (MDL), as commonly used, refer to a minimum incremental concentration or exposure rate based only on analytical or instrument sensitivity. In order to lessen confusion, the Environmental Measurements Laboratory (EML) usage[7] of Lower Limit of Detection (LLD) is recommended for the minimum detectable increase in sample counting rate. The LLD can be converted to a MDL by specification of an acceptable confidence level and conversion to sample concentration. A LLD for measurement of external radiation can be calculated in exactly the same way as for counting of samples; for such measurements the LLD and the MDL are identical.

A MDL for either a sample concentration or a direct measurement can be translated to an equivalent Minimum Detectable Dose by carrying it through an environmental pathway matrix.

Since both the background (C_B) and sample counts (C_S) (and rates) estimate central values of distributions rather than points, preselecting a lower limit of detection equivalent to ($C_S + C_B$) as some multiple of C_B implies the acceptance of uncertainty in evaluating a sample count. The total uncertainty is the sum of probabilities of Type I decision error (p_I) (accepting the presence of radioactivity in the sample when none is present) and Type II error (p_{II} failure to recognize the presence of a specified amount of radioactivity, the LLD, when it is present). For direct counting of a sample with no interferences, several reasonable assumptions permit the following derivation:

Assume: (a) Poisson counting statistics: standard error = $\sqrt{C}$

(b) Similar counting times for determination of (C_S+C_B) and standard error of C_B

(c) Standard error of (C_S+C_B) ≈ standard error of C_B for small increments of C_S

then, $C_S = (C_S+C_B) - C_B$

$$S.E._{C_S} = \sqrt{S.E.^2_{(C_S+C_B)} + S.E.^2_{C_B}} = \sqrt{2 \times C_B}$$

Let C_S = LLD, which can be set to some factor K times the standard error of C_S,

that is, $LLD = K\sqrt{2C_B}$

and $K = k_I + k_{II}$,

where k values are taken from the standardized normal variate probability tables for onesided errors.

It is Environmental Measurements Laboratory practice to use the term Lower Limit of Detection for the quantity here defined, that is:

> The Lower Limit of Detection (LLD) is the smallest true sample net count rate which, using a given measurement process, will be detected $100p_{II}$ percent of the time and the risk of falsely concluding sample activity is present, when it is not, is $100p_I$ percent.

Johnston[8], addressing the equivalent of a MDL directly and incorporating other sources of variability in the overall sampling/analysis scheme, derived an "Index of Adequacy" equivalent to this combined probability factor.

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*The alternative term "as low as reasonably achievable" has been recommended by the ICRP[2] and adopted by the Nuclear Regulatory Commission.

**Table 2 of Reference 5 gives dose equivalents for stated analytical levels. The levels given in that 1972 document and included in Appendix C of this document are readily lowered by most laboratories, especially for ^{90}Sr and ^{131}I.

It has been the practice at several sites to assign to the factor K a value of 2 (an approximation of 1.96) for a claimed 95 percent Confidence Level of detection. This may be standarized in a definition of LLD, and by implication the MDL, for reporting purposes, but with the recognition that a continued probability of 95 percent detection of positive results, by virtue of the relationship between the k's, has a corollary of false positive reporting for as many as one out of three determinations.

Pasternack and Harley[9] have extended the derivation to the much more complex problem of gamma spectrum analysis, pointing out that for such analyses the LLD for a given nuclide varies not only with the other nuclides present but also with the list of nuclides assumed to be present. No attempt is made here to provide standard MDLs, and for gamma emitters; comparability between laboratories will undoubtedly remain questionable.

The Sampling Equation. Potential methods of achieving a lower Minimum Detection Limit for a given analytical Lower Limit of Detection are indicated by the following sampling equation.

$$A = a\frac{tC}{Vfre}$$

where A = target concentration, the smallest concentration which will be quantitatively measured by the procedure

t = counting time devoted to a sample

C = minimum count rate measurable by the detector in time t

V = volume of the sample collected

f = the fraction (or aliquot) of the sample collected which is carried into the purification and counting steps

r = fractional analytical recovery (efficiency) for the radionuclide of interest

e = counting efficiency of the detector (fraction of a count per disintegration)

a = unit conversion factor

Values of the terms V, C, e, and r are all affected by available hardware, technical training, and operating expenses. Obviously, a broad range of combinations of these four terms will satisfy the requirement for measuring a given value of A. Neither the minimum cost combination nor the combination which can be most easily met with capability on hand is straightforwardly determined. In practice, several trial combinations and their implications should be evaluated in order to optimize the sampling and analytical procedures. Note that if C is set equal to the LLD, A becomes the MDL. However, the equation is valid at all count rates and concentrations.

In this analysis, the variabilities of other parameters deserve attention because their relative errors, especially for V, may be comparable to counting error. The chance of making improvements in counting statistics depends on the precision of the rest of the sampling-measurement system. For example, the volume of air pumped may not be known more precisely than ± 10 percent. In this case there may be little merit in incurring significant costs to make the counting procedure much more precise than ± 10 percent.

Program Specifics. Most environmental surveillance guides* devote one or more section to program design, using terms such as protocol, objectives and rationale. Yet few of these programs adequately specify such parameters as number of samples, sampling frequency, or methods of compositing. Some guides have suggested minimum numbers of samples and sampling frequency, but it is not wise to apply simple criteria to all facility types or sites.

One method of choosing criteria for sample collection--numbers of sampling locations per site, sample collection and/or analysis frequency, and whether to composite samples or analytical data is formal sampling theory.[10] An alternative is to base a program design on experience.

To do this, the 1976 annual environmental monitoring reports for 13 major nuclear sites within the U.S. were reviewed. Seven Department of Energy (DOE) contractor sites and six Nuclear Regulatory Commission (NRC) reactor sites were included. The DOE contractor sites were chosen on the basis of one site within the purview of each of the regional operational offices from ERDA 77-104 (Environmental Monitoring at Major U.S. Energy Research and Development Administration Contractor Sites, Calendar Year 1976), while the reactor sites were based on the availability of 1976 reports. Through this selection process it was possible to utilize the reported details from a wide cross section of facility types and geographic locations around the U.S.

The information extracted from these reports was grouped in one of three environments--atmospheric, terrestrial, or aquatic. This grouping was based on the "environment" most likely to be impacted by the routine effluents from each site. Only that sampling and analytical information considered part of the routine surveillance program at each site was included. Hence, precipitation collection, special one-time environmental studies, etc., were excluded. However, the importance of these media or parameters needs to be judged on a site-specific basis and should not be ruled out of an environmental surveillance program simply because of omission here.

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*See for example: ORP/SID 72-2, ERDA 77-24, Reg. Guides 4.1 and 4.8, NUREG-0475, and NCRP-50.

Findings. Tables 1-3 summarize the results of this compilation, giving the range and typical (median) values for the following parameters:

- Number of sampling locations per site
- Frequency of sample collection
- Number of analyses per sample collected
- Frequency of sample analyses (often different than the frequency of collection because of compositing).

In comparing the median number of sampling locations in Tables 1-3 with the "perspective" tables of Denham[11], it is clear that more than a single rationale exists for environmental sampling. On the other hand, those sample media which are difficult to collect or for which there are limited dose pathways (e.g., HTO or radioiodine in air), a relatively consistent minimum number of sampling locations is apparent. This approach was used to arrive at an acceptable minimum number of sample locations per site based on the calculated annual dose to individuals as the rationale. Similarly, the frequency of sampling and analytical measurement experience (Tables 1-3) of others provides a useful base from which to establish "frequency" protocol. A third item, compositing of samples or data, while not given explicitly in Tables 1-3, was discussed to some degree in several of the reports. Typically, some samples (e.g., air filters and milk) are composited over time (by location) to provide a larger sample and enhanced analytical sensitivity, while others (e.g., soil and water) are composited at collection prior to analysis to avoid major concentration inhomogeneity problems. Both are considered acceptable and useful techniques, yet the reasons should be examined on a case-by-case basis to ensure meaningful results from which appropriate interpretations can be made.

The previous discussions point to the fact that a weak link in environmental surveillance continues to be insufficient documentation of why and how samples are collected. Although sampling rationale was not explicitly stated in any of the reports reviewed, the following objectives, including the four primary ones cited by Denham[11], are suggested for consideration in program planning:

- Dose assessment
- Compliance with standards
- Verification of effluent controls
- Trend evaluation
- Public information.

Recommendations and Conclusions. To plan and conduct environmental surveillance programs on a minimum cost basis, it is essential that an appropriate list of rationale be established for that particular site. One method of establishing an acceptable minimum number of sampling locations (by medium) per site is to perform a critical pathway analysis. The doses thereby obtained should be compared with the recommended number of sampling locations given in Table 4. The same technique can and should be used for other rationale. It should be recognized, however, that these choices are not necessarily mutually exclusive (i.e., sampling at a given location may satisfy several rationales or different rationales may require different sampling locations for the same medium.)

Once the number of sampling locations has been chosen, the distribution techniques of Waite (BNWL-SA-4676), the EPA (ORP/SID 72-2), and Regulatory Guides 4.5 and 4.8, can be used. Another recent publication by Legett, et al[12] addresses a statistical methodology for surveying contaminated facilities. Many of the suggested methods are applicable to environmental surveillance.

It was interesting to note that several soil sample compositing methods are presently in use, ranging from a series of sample cores along a straight line to taking one at each of the 12 hourly locations on the circumference of a circle. However, no consistent depth of soil sampling is observed. This inconsistency remains, but a depth of 5 cm seems to be reliable and applicable to most soil types. This was not considered a serious issue since soil sampling is not recommended for dose evaluation.

Section 3.6 in the DOE Guide (DOE 77-24) should be consulted for an analysis of sample size, especially with respect to analytical detection levels and variability.

Similarly, Section 3.7 of the DOE Guide treats the topic of measurement frequency and is repeated here in total:

> "Aside from sample sensitivity requirements, the frequency of sample collection and measurement must take into account the half-life of the radionuclide being measured. Even though a decay correction can be made, a delay of two half-lives between sampling and analysis for an intermittent occurrence of a radionuclide in the medium being analyzed increases the probable error and thus the MDL by a factor of at least two, and probably more depending on the time of arrival relative to the time of sample collection. For a sample analysis with a barely acceptable sensitivity in any case, such an increase may be unacceptable."
>
> "Because effluent releases and the environmental media they affect may both vary with time, nonproportional and periodic grab sampling risk bias by being synchronized with some cyclic feature of the process or the environment (e.g., a liquid effluent release schedule, tidal cycles or daily fluctuations of stream flow). Synchronization (i.e., collecting an environmental sample either in or out of phase with effluent releases) may be desirable if the sensitivity of the monitoring system can be increased, but inadvertent synchronization should be avoided because the resulting bias may lead to misinterpretation of the results."

TABLE 1. SUMMARY OF ENVIRONMENTAL MONITORING PRACTICES--ATMOSPHERIC PATHWAY[11]

	Particulates	Tritium	Iodine	Direct Radiation (TLD)
Number of sites	13	5	8	13
Number of sampling locations	1-29 (12)*	3-29 (7)	3-12 (7)	4-53 (24)
Number of analyses	3-6 (4)*	1	1	1
Sampling Frequency				
Daily	2			
Weekly	2-11	1	7	
Biweekly	1-3	2	1	
Monthly	1	2		7
Quarterly				7
Semiannual				2
Annual				1
Other				1
Analytical Frequency				
Daily	2			
Weekly	3-11	1	7	
Biweekly	3	2		
Monthly	1-8	2	1	7
Quarterly	1-4			7
Semiannual				2
Annual				1
Other				1

*Typical or median value for those sites collecting and analyzing the respective media shown.

TABLE 2. SUMMARY OF ENVIRONMENTAL MONITORING PRACTICES--TERRESTRIAL PATHWAY

	Soil	Vegetables and Grasses	Forage	Milk	Animals
Number of sites	12	9	3	11	7
Number of sampling locations	3-28 (12)*	3-25 (12)	2-14 (5)	1-13 (5)	1-14 (3)
Number of analyses	1-4 (3)*	1-5 (3)	2-4 (3)	1-5 (3)	1-3 (2)
Sampling Frequency					
Daily					
Weekly				4	
Biweekly				2	
Monthly	1	4	2	8	1
Quarterly	1	2		1	
Semiannual	1	1			1
Annual	9	9	1		5
Other					
Analytical Frequency					
Daily					
Weekly				4	
Biweekly				2	
Monthly	1	4	2	9	1
Quarterly	1	2		4	
Semiannual	1	1			2
Annual	9	9	1		5
Other					

*Typical or median value for those sites collecting and analyzing the respective media shown.

TABLE 3. SUMMARY OF ENVIRONMENTAL MONITORING PRACTICES--AQUATIC PATHWAY

	Surface Water	Ground Water	Drinking Water	Sediment	Fish/ Shellfish	Plants, Waterfowl, Etc.
Number of sites	12	9	10	11	11	9
Number of sampling locations	2-15 (6)*	1-75 (6)	1-16 (3)	1-24 (4)	1-10 (3)	1-31 (3)
Number of analyses	2-9 (5)*	2-8 (4)	2-8 (3)	1-6 (3)	1-4 (2)	1-3 (2)
Sampling Frequency						
Daily						
Weekly	5		3	1		
Biweekly	1					
Monthly	7	5	6	1	2	3
Quarterly	2	4	2	1	4	
Semiannual	1	3	1	5	4	2
Annual		1		3	1	4
Other			1			
Analytical Frequency						
Daily						
Weekly	1		3	1		
Biweekly	1					
Monthly	9	5	8	1	2	3
Quarterly	8	5	4	1	5	1
Semiannual	1	3	1	5	4	2
Annual		1		3	1	4
Other			1			

*Typical or median value for those sites collecting and analyzing the respective media shown.

TABLE 4. RECOMMENDED MINIMUM NUMBER OF ENVIRONMENTAL SAMPLING LOCATIONS PER NUCLEAR SITE AS A FUNCTION OF CALCULATED ANNUAL DOSE TO THE MAXIMUM INDIVIDUAL*

	Calculated Annual Dose Level (mrem)			
Environmental Media**	1-10	0.1-1	0.01-0.1	<0.01
Air, ambient radiation	10	3	1	0
Milk, other foodstuffs, water, fish	5	2	1	0

*These criteria are for a dose based program, but are assumed to be equally applicable for other rationales, such as compliance and public relations. At higher dose levels (e.g., 10-100 mrem/yr), increase the number of locations by a factor of 3 for each order of magnitude increase in the dose or factor of 10 for each factor of 100 increase in the dose level.

**Other media, such as soil and sediment, which are not part of a direct-dose pathway, are excluded (i.e., not required as part of the environmental program). However, there may be other compelling reasons to include them, in which case soil should be added at the same level as air; sediment at the same level as water.

"Seasonal habits of people and animals can also result in nonrelevant data from a uniform year-round program. Recreational exposures are an excellent example, for aquatic sports as well as hunting and fishing. Aquatic and terrestrial biota can be selective in what they eat and they select differently according to availability. For example, assessing the dose impact via milk cattle forage requires sampling in the season the forage is eaten. The temptation to take either random or a complete series of samples for such a purpose, based solely on an arbitrary schedule such as every six months, should be resisted because the data may well be of no value in pathway analysis. Although such data may be suggestive, they are not likely to be reliable."

Another consideration relevant to compositing is that it is characteristic of environmental monitoring data that many results occur at or below the minimum detectable level. For reporting and calculation of averages (see the last section in this chapter for a discussion of acceptable methods of data analysis), it is imperative that these facts be considered. When results of all samples are grouped according to analysis type, means and standard deviations of these results can be calculated. The standard deviations so calculated of these grouped data represent total sample variability rather than merely analytical variability and are the values recommended to be reported.

Sampling Representativity

Environmental Variability. Concern about whether data are representative expresses an intuition that composition across an environmental compartment might not be uniform. Less intuitive are factors about actual degree of nonuniformity and about how large a degree of nonrepresentativity one may be willing to accept in the data. Degree of nonuniformity concerns the material substance of interest whereas representativity per se concerns our motives for wanting to know anything at all in a quantitative way. These two aspects of representativity will be contrasted throughout the following discussion.

We worry whether the data are representative because our interests extend beyond the data themselves. We wish to use the data as a springboard to reach conclusions about something we did not sample, perhaps for reasons of inaccessibility or costs. Our springboard will contain a logical basis that can be reviewed and refined at will, but we worry that the data that go into the major or minor premises might be faulty--nonrepresentative--so that we might be led to incorrect conclusions. We want to use data from a small part of the physical world to calculate the "facts" about a larger and possibly different part. Data are said to be representative if the calculated "facts" are similar to the larger reality in a practical way.

In these guidelines emphasis is on the situation where the mass of the sample may be only a millionth or less of the mass of the environmental compartment it is intended to represent. Additionally, there is a dynamic aspect. We would like to reach some conclusion that the sample can tell us about its source (historical point), or what might be inferred about events yet to come (projection in time), or about events that went on in an adjacent area at the time the sample was collected (geographic extension). Finally, we may combine the field data with demographic data and with information about biologic effects in order to describe an impact.

The issue of representativity is important, as the impact might be serious so, being sure of what the data really represent, and what they do not, deserves the highest priority, higher than the priorities of accurate chemical analysis that usually bear the burden of accusation when the data "just don't look right".

How May Environmentalists Approach "Representativity"? Representativity, of course, is something that happens in the field when the sample is taken. That is, the field operations and technique will determine how reliably the sample represents a part of the environment we are interested in. However, representative sampling does not begin in the field--it only ends there. To achieve representativity one must start at the beginning. That beginning is a debate about what we really want to learn of the environment and of how sampling might play a role in that learning process.

For most persons concerned about environmental degradation, the ultimate question concerns the item called "impact", a net result of all the factors involved--a measure of how severely living space has been affected, might have been affected, will be affected --. For example, the mining industry has an analogous "bottom line" to "impact"--value of the rock. And as the value of a rock cannot be determined by sampling alone, no matter how good or representative, neither can impact be measured by sampling, good or bad. Of course, neither value nor impact can be reliably estimated without good sampling. This emphasizes that all of the factors which go into the logic net and the calculations too, must form a coherent and intercompatible assemblage. The requirements on the sample and thus also on the field techniques which yield the samples, must be rooted in the coherentness of the entire assemblage of factors. Several programs to assess impact can be proposed for any specific combination of contaminant and geography. More than one can be right in the sense that the derived conclusions would not be misleading beyond the statistical certainties. They would differ in cost and emphasis. It is important that the sampling requirements for one program are not thrust into the logic set of another program with which it was logically ill-suited. Such would be one form of nonrepresentativity.

To be more concrete on this point, in a network of samplers one intends that all the space between samplers is "represented" by at least one sampler. That is to say, in the calculational model the data recovered from one sample point will be applied in some way to the space between that point and the next sampler. There are several ways to do this mathematically: interpolations may be linear, parabolic, logarithmic, step function, etc. Which kind of interpolation is used can be debated according to what is known or suspected about dispersion, etc. The actual choice for interpolation will determine, in part, what kind of sample spacing to use. As a general rule, data are more accurately interpreted if the incremental values between data from adjacent sampling points are similar in magnitude as used in the model. Thus, a linear interpolation would lead to equal spacings between sample sites or sampling times, whereas a logarithmic interpolation which is linear in logarithmic units, would be better served by placing the sample sites closer where the concentration gradients are steeper (in absolute, not logarithmic units). Specifically, in the latter case, for a logarithmic concentration field the sample sites would be optimally located if/when the data values among them varied in a way that their logarithmic increments (not the absolute ones) were equal. To the degree that this is achieved one may minimize the number of sample points needed to calculate, with a preselected statistical certainty, the inventory of material in the field. We should expect there to be an economic drive to apply similar techniques because once the gradient type is known the number of samplers required to measure the gradient can be reduced to a minimum number, commensurate with the degree of statistical precision desired in the calculated result.

Summary. Representativity is achieved when the calculated results based on the samples and the logic net correlate well with the physical world. In addition to motives for being accurate about the calculations and derived implications, there are economic incentives to bring the sampling into a good alignment with the most realistic model. In that way the number of sample points can be minimized, thus minimizing the cost/quality factor for the surveillance.

Representativity in sampling is not simply a matter of good technique in the field, although that is essential. But still more crucial is for the sample taking to be consistent with the calculational model and its logical correlates. It is the model, not the samples, which represents the physical world. The samples/data merely serve to calibrate the model. Multiple models might be useful in a specific situation and they may require different sampling programs. If only one sampling program can be carried out the inappropriate calculational models would be avoided. Representativity begins with a precise statement of what sort of information is required from the field samples. Field technique is only the last step in the chain that yields representative samples.

Verifying that representativity has been achieved or missed deserves considerable deliberate effort. Environmental issues are usually without a referee, hence the verification must be approached through indirect means. These include attempts at disproving that an alleged situation actually exists. The subtleties of logic for proof versus disproof are important to this issue. Acquiring data on a temporary basis in order to pursue a choice between alternative interpretive models should be aimed at crucial tests of the differences between those models.

Establishing a Reliable Baseline. The motives for establishing a baseline hinge on quantitative results. Perhaps one wishes to know in a simple way "how much is out there" without regard to past or future measurements. In that case, a simple central value would be adequate, even if there were actually a considerable range of concentrations, and it could be obtained by simple grab sampling. Perhaps instead one wishes for a reference against which past or future measurements can be compared. Then, some time factor must be brought into the sampling and also into the theory used for extrapolating outside the realm of sampling. Alternatively, one may wish for current data on background to use in assessing current impact on an effluent, a situation that requires decision about which samples of a set were affected by an effluent, or, if all were suspected to be affected, assessing the relative amounts.

It is useful in this discussion to distinguish the meanings of "background" and "baseline". Background refers to the reality of lower concentration levels of a contaminant as it exists at any time, whether measured or not. Baseline means a numerical approximation of the real background. Baseline is the thing compared with measured concentrations to assess whether they exceed background.

Whether a baseline is reliable will depend as much on one's needs as on the facts. Specifically, how precisely must extrapolations or comparisons be in order to be serviceable? How does the time interval involved compare with the periods of natural fluctuations of either background or strength/direction of the effluent source. How much resolution is desired compared to the costs of acquiring more resolution?

Three aspects of a baseline will be described in more detail. First is concept--precisely stated concepts--about what the baseline is intended to represent, when it is to be applied, and what form the numerical data should have. Second is measureability. A central value will not be enough if there is intent to use the baseline for comparative assessments about whether a new item of data belongs to the background, or how much it deviates from the background. Such applications require that variance be known and one needs also to know if the variance changes with time or if it is different from place to place. Third is contrast between the baseline range and the arguable increments of contamination. If the nature of the effluent is to be either very high in concentration relative to the background or very low, then simple facts about the background will suffice. However, if the effluent concentrations are serious considerations even when near background levels then not only does one need to know the background variance to good precision, but methods for minimizing the uncertainties due to that variance should be used.

Baseline Model. Baseline is a concept, not a part of the physical world. It belongs to the calculational models. There, it may variously represent (1) pristine concentration that existed before there was an artificial impact, (2) a normal level of effluent against which one looks for excursions, (3) a level existing for nonlocal reasons when one is interested in the local situation, (4) a background level due to multiple local inputs, and, there may be others. Data one might bring into the issue serve to calibrate the concept with respect to the physical world. Establishing a reliable baseline involves concepts from the section "Representativity", including a precise description about what sort of baseline might be appropriate for a specific situation.

The term baseline is somewhat misleading. Not only is the concept used in a plurality of ways but also the real-world concentrations to which it refers are not regular. Consequently, the conceptual baseline, which would be easier to use if it were simple, must suffer some degree of mismatch with the range of physical concentration it is intended to represent. Thus, "reliable" has much to do with the appropriateness of the model to be used.

Deciding which sort of model to use for baseline begins with concepts about how the contaminant at issue enters the environment, accumulates, and is consumed. Some materials degrade so slowly that their buildup can be monitored. Plutonium in soil is an example. Other materials, like tritium or DDT degrade measurably so it is possible for their buildup to reach a steady state or even decline. In such a case it is the flux of material through the environment, rather than the amount, that might be of greatest pertinence to an assessment program. For others, like iodine and xenon, which are still more ephemeral, their concentrations at selected points may yield patterns along a time dimension that carries both a baseline quality and a record of events. Materials like NO_x and photochemical smog yield patterns that reflect weather conditions as strongly as they characterize the sources of effluent. For them the concept of background is obscure since to a degree they are the environment and people who live with the problem are concerned with the absolute value of the concentrations more than with the value at one time relative to the value at some reference condition.

Setting up a reliable baseline begins by getting the issue onto a conceptual right foot. Does the model call for increments, for flux, or for concentrations? Whatever, the baseline must match. Furthermore, the baseline must be measureable. Concentrations can usually be measured readily, but increments and fluxes may require several coordinated samples, each of which provides a concentration, in order to get one estimate of flux or increment. This is to say, the environmental model should be not too sophisticated. Even though logically elegant, if key data for a model are difficult to obtain, then its reliability will suffer. There is a trade-off here between representativity and reliability. A model which is astutely representative may not be reliable in practice if the required inputs of data are too difficult or costly to obtain.

Obtaining a Central Value and Variance. Once the conceptual baseline has been established, then work may begin to calibrate it. The form of the baseline would be defined by the terms of the model and there are several possibilities: (1) a single numerical value. A ± B to be applied at all times and at all sample points, (2) single values for each sample point and having the form A ± B, but with tailored values of A and B for each sample point, (3) time-variable values based on circadian or monthly or seasonal systematics about the concentration of the monitored material. The variability may be applied uniformly to all sample points in the net as in case (1) or selectively as in case (2). How much complication is put into the definition will be determined by how intense the differences are between sites compared to the impact to be measured. The simpler forms of baseline are easier to use and discuss, but they may be lacking in fairness. Thus, the degree of complexity to use may be a topic for debate and there may be a trade-off between utility and accuracy.

If plant operations have not yet begun then the measurement of background may be uncomplicated. There may be advantages to studying the background in much detail, not only to clearly measure central value and variance, but also to find patterns in the mechanisms which disperse the material of interest so that the finally selected locations of samplers may be more astute. At this stage there should be an intent to refine any supposition about dispersion modes and adjust the monitoring program according to improved concepts. Baseline dispersions of trace materials will show patterns. The complexity of those patterns depends on many local factors. Work done to establish baseline should proceed until the features of those patterns become clear. These features may be statistical in nature, or they may be cause/effect. The reliability of the baseline will be proportional to the clarity with which one can describe the patterns of the background.

If plant operations are already underway then baseline can still be quantified, but there will be some constraints about how to arrange samplers and select data. There is little complication for liquid effluents since the inputs and outputs of a plant are separately accessible. If discharge is into a stream, then upstream and downstream sampling will simultaneously obtain data for both background and additions but questions of mixing and lack thereof are serious. For air discharges a remote location may be used to assess background, but representativity may be suspect. Features of context, geography, weather, and other factors partly measure the suitability of a remote site and it must not possess confusing attributes.

Obtaining a measure of background in the face of active contaminating events can be done. How it may be done, validly and precisely, depends on local situations to such a degree that general rules would be dangerous advice. Some local quirk, ignored in the phrasing of the general rule might invalidate the scheme. Yet, the need for a quantified baseline may justify attempts at its measurement that are served by nonstandard arrangements of data. An example of this kind of approach will be given for the case of air samplers surrounding a single source of contaminant. The purpose of showing this method is less a specific formula for how to sample around particular sites than it is a qualitative example to show how data from samplers that are affected by effluent can be used also to extract information about background. This method gets dual use from the data. That is, this method arranges the data so they simultaneously indicate background and contamination, quantitatively.

Fractional Exposure Method. The principle of the method depends on (1) the different samplers being exposed to the effluent-laden air for unequal amounts of time during a sampling period and (2) the rate of effluent discharge being somewhat uniform. By using a wind rose constructed for the period of sampling the sample points can be evaluated according to the percentage of the total period they were downwind from the effluent source. Then, a graph is constructed of concentration versus percent of time exposure. If the effluent truly is measurable and adds to the background, then the scatter diagram of plotted points in the graph will have a slope that can be evaluated statistically.

There are several important features in such a graph, which are shown in Figure 1. A straight line may be fitted to the data according to some method like least squares; the line will have both a slope and an intercept. The value of the slope can be tested by statistical means against the value zero (no slope) to assess whether the slope (hence impact) is statistically significant. If the slope is statistically indistinct from zero, then all the data may be combined directly to yield an estimate of background. If the slope were statistically different from zero, then the calculated intercept (at zero percent exposure) is one estimate of background. Successive estimates of background provide data for a baseline.

Contamination level can be estimated at each sampling point by subtracting the value B from the apparent concentration. Impact could be assessed either through an integration among the individual contamination levels as fitted to their geographic and demographic locations, or through the slope of the line, adapted to a model based on wind data and demography.

The graph has interesting properties. Note that it yields an estimate of background even though no sampler is in a background condition for the entire sampling period. Additionally, the estimate of background will have a lower statistical variance than the individual data points do because the slope of the line is established by several data. There may be an uncertainty about the background estimate due to the difference between extrapolation and interpolation but it will not be serious because the extrapolated distance usually will be small and because conceptually one is confident that a finite background truly exists. At the other end, extrapolation to 100 percent exposure yields the best estimate for the theoretical concept of continuous exposure.

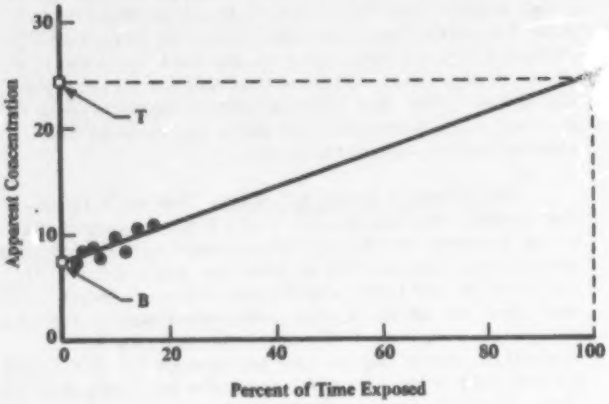

FIGURE 1. SIMULTANEOUS ESTIMATE OF BACKGROUND AND CONTAMINATION FROM ONE DATA SET

Figure 1. Data for air concentrations (dots) are plotted versus percent of time the wind blew from a source toward the sampler, as determined from a wind rose (not shown) constructed for the sampling period. Background (square B) is estimated by the intercept of a least-square linear fit to the data. Square T represents the concept of concentration at continuous exposure.

The procedure above is capable of being refined in several ways to make it fit better to local circumstances. The first refinement might recognize that the different air samplers are not at the same ranges from the source. Thus, for a better comparison the data values obtained at each point could be adjusted to what they might have been if they were at a standard range from the source. Typical factors of atmospheric dispersion would be applied here to inflate or diminish the data value prior to plotting it in the graph, depending on whether the samplers actual position was further or closer than the "standard" range. Additionally, the diffusional mixing that goes on naturally in the winds might not have been similar in all directions or at all times. So far as data can be mustered to this issue the measured concentrations can be adjusted and the adjusted values applied to a graph of the kind described. Obviously, this method can be applied at any time in the history of a program. Even if a baseline were established before operations began, this approach provides a way to assess whether the baseline still is appropriately calibrated.

This methodology has also a substantial tactical advantage in that it forces a clear assessment of how successfully a plant's impact was measured in each sampling period. A clear indication is given about whether the sampling program itself is adequate to detect an impact. For example, if the calculated slopes on the graphs were repeatedly not different, statistically, from zero, then one would be forced to conclude that either the plant was (a) practically clean or (b) the monitoring system was not sensitive enough to measure its effect. The same data can be used to calculate a variance which could be compared with the variance expected from background--either from professional judgment or independent measurements. If the calculated variance were relatively larger, then one would be led to accept conclusion (b) over (a), and changes in the sampling/interpretation program could be entertained.

Note that in this method each item of data participates in both a measure of contamination and an estimate of background. Compared to the alternative of using remote samplers for estimating baseline there are several advantages. No extra samplers are required, so costs are less. There can be no quarrels about whether the baseline data are biased for reasons of nonrepresentative geography. And, the background data are timely, each background estimate applies to the identical time period as involved with the sampling of impact.

Contrast. Recognizing a real increment of contamination in the face of a variable background may require more than a good knowledge of the background variability. This situation requires special methods if the increment of contamination that is looked for happens to be on the order of the size of the background variability. If the background variability conforms to a Gaussian distribution then elementary statistical tests for a suspect datum belonging to background can be made without complication. For more difficult situations there are additional treatments of the data that enhance the contrast between background and a contamination. These are discussed elsewhere in this document.

Summary. Reliability of a baseline depends jointly on the established facts about background concentrations, the details of concept regarding variations in background, and the contrast displayed when data are compared to the baseline. The contrasts can be assessed by statistical methods, but they may be of the most simple kind unless near-background contamination levels are of concern. The contrasts may be enhanced either by reducing the effective variance of the baseline or by transforming the data to a form that is amenable to statistical tests that are more valid or more precisely applicable.

As the facts about background concentrations are learned, concepts about the baseline (as a model) deserve to be refined and the results translated into a more astute distribution of samplers, followed by a more precise interpretation of the data they return. Knowledge and concepts about the movements of contaminants may be revised as new data are obtained on background and contaminants. Proposed revisions to currently used concepts can be encouraged throughout the sampling program and new data used to demonstrate their values. In this way the representativity of future data can be pushed to a high degree.

Data Analysis

Data acquired during a data collection interval may be grouped according to geographical location, media sampled, nuclide sampled, or time of sampling. (Such groupings are based on physical considerations or specific program objectives rather than on the actual data values obtained.) The analysis and characterization of each of these data groups constitutes a major emphasis in the data treatment. Characterization may be graphical or numerical, but usually involves determination of statistics which estimate central value (average or arithmetic mean, geometric mean or median, mode, midrange) and dispersion (range, standard deviation.) Determination of these statistics and further data comparisons are often simplified by graphical analysis if the data conform to some standard distribution.

Skewed and mixed distributions, along with the presence of outliers and of less-than-detection-limit values, are general features that pervade environmental radiological surveillance data. The analysis and subsequent reporting of surveillance data having these features are not easy or routine. Moreover, the same analysis procedure may not apply to different data groups.

One intermediate goal in environmental data analysis is to characterize the value of some parameter in a portion of the environment over some period of time to a stated degree of accuracy from a limited number of data points. The following general principles apply:

- One datum provides an estimate of the parameter value, but in nearly all practical cases has such a large uncertainty associated with it as to be in itself of little value.
- Spatial and temporal variations have significance to be determined on a case-by-case basis. In trend indication, for example, spatial variation may have no significance, but extraneous sources of temporal variation are highly important. For an inventory of accumulated radioactivity in the environment, temporal variation may have little significance, but spatial distribution is critical. For dose estimation, as a basic goal, both spatial and temporal variations are important, since annual averages of exposure to a distributed human population are desired.
- Completely random sampling (or measurement) is neither astute nor economic for environmental programs. Continuous sampling may satisfy needs to account for temporal variation. For spatial distributions stratified sampling and subgrouping of results are commonly used but require *a priori* assumptions.

Estimates of Precision. The overall precision estimator, the variance (S^2), equals the square of the standard deviation (S). Note that estimates of the variances may include nonidentified systematic or cyclical errors.

Then,

$$S_T^2 = S_a^2 + S_t^2 + S_s^2 + S_n^2 + S_p^2 + S_m^2$$

where the subscripts denote:

T = total
a = space
t = time
s = sampling
h = sample handling
p = sample processing
m = measurement

The degree to which these components can be quantified and separated determines in part the sensitivity of the measurement system for detecting the presence of a contaminant.

Estimates of the magnitudes of some combinations of variance components may be obtained from replicate measurements, either as part of the routine quality assurance program or from specifically designed sampling and analytical experiments. Such experiments should be performed adjunct to routine environmental monitoring, both to assure that observed variances are pertinent to the monitoring system and to make the studies more cost effective.

Results of replicate samples intended to measure variance inherent to the environment (S_a^2 and S_t^2) should be treated cautiously, since these components may be divisible into subcomponents for time (both short and long intervals) and for scale of geographic association with the facility being monitored (local versus regional). There is a continuing risk that the differences between environmental variance locally and regionally may be wrongly assigned, biasing the apparent impact of local operations. Similarly a normal seasonal effect may be wrongly interpreted as a change in environmental impact.

It has been common practice to report only a multiple of the standard deviation of the sample count (the square root of the variance S_m^2 above) as a measure of uncertainty of an environmental datum. S_m^2 is better known routinely than all other variances, and frequently the only one quantified. Each analytical result provides its own measure of S_m^2, undoubtedly a major reason for its popularity. Unfortunately, this is often the smallest of all components of variance, so that the unqualified use of S_m^2 alone yields an unwarranted impression of overall statistical confidence in the reported concentration. This can be particularly misleading when reporting an average of a group of data, with the standard deviation of the average adjusted for the number of data points.

Ideally, all components of variance should be quantified in order to identify causes of variability which warrant and are susceptible to improvement. For practical purposes, estimates of variance from a sufficiently large number (at least ten and preferably more) of data points may be satisfactory. For groups of less than five data points, such estimates are of little value; lacking other information, only precision of measurement can be given. In either case, the basis should be clearly identified.

> Testing for Homogeneity. "When seemingly extreme observations are obtained, the question always arises whether these observations should be considered discrepant and rejected. Points of view range from the flat statement that "data should never be rejected" to the view that it is not "practical" to include any suspicious measurement, regardless of the fact that the suspicions arose as a result of the examination of the data. Both points of view have their merits; often the single discrepant observation contains the most significant information of the group. On the other hand, this information may be completely irrelevant to the question that the data were originally supposed to answer. For example, one discrepant analysis in a group of five may give pertinent information with regard to difficulties present in the analytical method, but may also bias the analytical result if included in its calculation."
>
> \- Bennett and Franklin [13]

In addition to the general problem in the referenced quotation, environmental program managers are faced with the question of initiating investigative action or even halting facility operation on the basis of environmental data. The probability that a single environmental data point would imply an immediate risk of population doses exceeding the established limits is considered extremely low in the absence of prior and supplemental data. If such an occasion does occur, the assignment of cause and an indication of needed corrective action would be expected to be straightforward. Far more frequent are those "out-of-pattern" data points which may or may not reflect changing environmental or operating conditions, but which if accepted, will distort the eventual evaluation of environmental impact. How intense and prompt the follow-up efforts may be depends both on the initial believability of the datum and the seriousness of the problem it might indicate. For example, a requirement that a search for cause be made for all values exceeding two times the standard deviation implies that on average at least 2-1/2 percent of all data points should be investigated. The bulk of these data will be related only to ordinary variations in the processes. Accordingly, the standard response to values between the mean value plus two to three times the standard deviation level could be casual and nondisruptive of operations. At the other extreme, response to values exceeding the mean plus four times the standard deviation should be quicker and more intense. Since there is only a vanishingly small likelihood that such a relatively large value, if real, is the one observation in 31,000 expected during normal operations, serious consideration might be given to shutting down or isolating the offending operation. Intermediate concentrations may merit an intermediate kind of response.

At one site, better than 90 percent of those few data points which, on initial inspection, appeared suspicious were found to be due to obvious computational, measurement, or sample processing errors. Such immediate review of incoming data and feedback to the field measurement or sample-processing staff by an individual familiar with the program and past results is a most valuable adjunct to the program. However, a few measurements remain which cannot be explained and which suggest casual effects. Each program has its own rules for level and scope of follow-up investigation of apparently discrepant results; sometimes different rules apply to different kinds of data. Frequently, such rules are based implicitly on some statistical property such as range or median value. No single rule or set of rules is recommended, but more formal statistical techniques are suggested as an aid to a decision that a particular result is or is not anomalous.

Numerical Tests. If the distribution of a given set of data and measure of dispersion (standard deviation) or standard geometric deviation has been established, a new data point, as discussed early in the Data Analysis Section, can be tested for fit to that same distribution by standard statistical tests. A t-test is the most common means of estimating the probability that the given data point is part of the same distribution.

Nonparametric tests, involving generally some function of the range of the data set, are also available, although less efficient (in the statistical sense of the precision of the estimate) if a standard distribution fits the data. References 13-15, as well as other statistical references, give range probability tables.

Sequential Plots. Sequential plotting of data points as generated, even if no particular statistical distribution is assumed, has the potential advantage of revealing trends or periodicity in the data. Even more useful, once sufficient data)(at least 10 and preferably as many as 50 points) have been accumulated to establish a central value and measure of dispersion is a graph similar to the familiar control chart used in quality control. Such a graph, showing confidence intervals (multiples of the standard deviation) minimizes wasted efforts on values that are seemingly higher than usual but which may not be statistically different. This is especially useful when the data, like so much environmental data, is distributed log-normally.

A modification of the simple control chart is aimed at improving the detection of trends. Trends in the data may exist entirely below selected action levels, and indicate either incipient process control problems or degraded procedures. The search for such trends can be facilitated by plotting a running average in a control chart. The reduced scatter results from plotting the geometric mean of a series of data points rather than single values. Specifically, each plotted point is the geometric mean, appropriate for log-normally distributed data, of for example, three weeks data.*

The reduced scatter yields not only a simpler curve, but also a more sensitive indicator of small persistent anomalies. Because the standard deviation for the average of a group of data is smaller than the standard deviation for single values, the action level for a running average can be set closer to the average value.

The assumption of normal (Gaussian) distribution is often made, if only implicitly, since the associated statistical parameters and procedures are most familiar and most sample counting data can be treated satisfactorily** in that way. However, experience at several laboratories indicates[16] that much environmental data more closely fit a log-normal distribution, which after a logarithmic transform, can be treated as a normal distribution. Other recognized distributions have been identified with specific data groups. [17,18]

When data of one set number fewer than 10 or $S_g < 1.3$, no assumed distribution is likely to be superior to another as judged solely on the data. In this case, treatment of the data as distributed either normally or log-normally is unlikely to have a high confidence level. Dividing the group into subgroups may result in still lower levels of confidence. Averages can always be obtained by calculation, and standard deviations for small numbers of data may be estimated partly on the basis of distributional assumptions as derived from experience, treating small groups in ways most appropriate for larger groups that clearly come from a particular distributional form.

Numerical methods are available for testing the fit of data to at least the simpler distributions. The familiar χ^2 test is such a test for normality, or for log-normality after a logarithmic transform. However, the process can be laborious with sufficient data points to provide confidence in the result. Graphical procedures, using probability graph paper, may save not only time and labor but have other benefits as well. In addition, the numbers of data most conveniently treated with graphical methods correspond to the most common frequencies of data grouping for annual reporting purposes.

Probability Plotting. Probability paper is available commercially in several forms, but the normal (Gaussian) and log-normal are most commonly used for environmental data. Datum-percentiles are ranked and entered onto the probability paper. As a group, they should trend along a straight line; the usual visual test for a straight line trend is subjective, although least-squares fitting procedures are available for at least the normal and log-normal distributions. Linearity verifies the assumptions and (a) the grouping is homogeneous***, and (b) the distribution corresponds to the kind of probability paper used. A text by Hahn and Shapiro[19] is a useful reference for probability plotting.

When data are plotted, some variation will exist about any straight line because of statistical fluctuations. A best-fitted straight line drawn through the data yields values for median and standard deviation, the median by the fiftieth percentile intercept and the standard deviation by the slope of the line. With normal (linear ordinate scale) probability paper, the median gives the geometric mean and the slope gives the geometric standard deviation.**** From these, the arithmetic mean and normal standard deviation can be calculated.[20]

Asymmetric Case. In the asymmetric case, the first consideration should be to explicitly relate the measure of central tendency to the actual uses to be made of the measure. Based on selecting an appropriate measure for the "center" of the distribution. It may be more informative to give a selected number of different estimates so that a clearer understanding of the information is possible.

One common way to proceed is to transform the concerned data, e.g., by logarithms, so that the transformed data appear symmetric. Then the center is estimated for the transformed data and the estimate (if desired) transformed back. This does not necessarily eliminate the problem of defining the best central value of an asymmetric distribution for the intended use. If this procedure achieves symmetry, any of the mentioned estimators may be used.

Standard Deviations and Other Estimates of Dispersion. In addition to estimating the center of the distribution, some measure of the spread of the data around the center is also informative and useful. Alternate terminology for the spread is precision, dispersion, or variability. Regardless of the terminology, the idea is to measure the dispersion of the data about the center. Again the symmetric and asymmetric cases must be differentiated.

The most familiar measure of dispersion is the standard deviation. Like the mean, it is not resistant to the presence of outliers and is difficult to interpret if "less-than" values predominate. In particular, large outliers tend to unduly inflate the standard deviation estimate. It has the advantage that standard statistical tests and tables are readily available to use with it when it can be validly estimated.

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*The number of data used in a running mean involves several trade-offs that must be made by persons handling the data. Too few data will achieve only a minor reduction of scatter compared to plots of single data; too many data points per mean value make the running mean insensitive and cumbersome to use.

**Since Poisson distributions applicable to counting statistics approach a Gaussian distribution with a large enough count.

***The members of a homogeneous group are collectively described by a single central value and a variance, each datum being an valid estimate of the central value.

****$S_g = X0.8413/X0.50$ or $X0.50/X0.1587$.

The commonly used sample range, based on the maximum and minimum sample value, is extremely sensitive to outliers, but requires no assumptions as to distribution of the data. The interquartile range is given by the difference between the 75th and 25th percentile points and is a resistant estimator. Note that 50 percent of the data occur between the two percentile values.

Another not so commonly used estimate, but one that is resistant and efficient, is the median absolute deviation. This is computed by subtracting an estimate of the center, preferably a resistant one, from all the data values, taking the absolute value of every difference, and then finding the median of the absolute values. Reference 9 gives an example of its use.

Distribution Analysis. In view of the many potential causes of perturbation in a group of environmental data there is no basis for assuming in advance that the data will follow any standard statistical distribution.

Handling of "Less Than Detectable" Values. The direct use of "less-than-detectable" values should not be reported. However, since extensive data exist in this form, it was thought useful to include applicable methodology.

If a large fraction of a data group shows less-than-detectable (LD) concentrations, special considerations are needed to determine a central value and measure of dispersion. Such groups of data are termed censored.

There is a significant difference between censored and truncated distributions. Both terms concern situations where some individual values are not known, either because they are beyond the range of measurement or because values beyond some limit have been rejected. For censored distributions the number of data points beyond the limit is known. For truncated distributions the number of such data points is not known. Obviously, percentile values can only be assigned to data in censored distributions. Grouping of environmental data should always yield censored, not truncated, distributions, i.e., at least include the information that a "less than detectable" result was obtained for the sample.

For conservatism, the assumption is sometimes made that all LD samples actually had concentrations equal to the detection limit and a group average is computed accordingly. Since this choice severely biases the computed average, it should be avoided. Other artificial rules for averaging LD values, such as setting LD or net negative counting results to zero, or applying a factor to LD results, also cause biased averages. Hahn and Nelson [21] discuss various methods for treating censored data.

One method [22] of group averaging of mixed positive and LD values is to average all values, including negative ones. By pooling the variances of the individual results, a detection level for the average can be calculated. Although the procedure is laborious for a large group of data, the approximation may be asserted for identical variances for each data point, in which case the uncertainty of the mean can be quickly approximated by the relationship:

$$\text{Uncertainty of Mean} \approx \frac{\text{S.D.}_i}{\sqrt{n}}$$

where S.D._i is the apparent standard deviation and n is the number of data points. The detection levels for the average and individual results are similarly related for the same confidence level. If only a few positive values are included with a large number of LD values, the average may still have to be reported as a LD value.

A preferred method for handling LD values involves probability plotting. As described earlier, the data are ranked by size, assigned percentile values and plotted on probability paper. The LD values span a range of percentile values in accord with the fraction of the group they represent. The positive values are plotted in their respective percentile positions and a best straight line is fitted through them ignoring the misfit to the LD values. As before, the slope* of the best straight line yields the standard deviation, and the geometric mean value or median, is obtained from the intersection of the 50th percentile with the fitted line. This method succeeds even when more than half the data are less than detectable, since the fitted line can be extrapolated to the 50th percentile in any case. Note that when more than half the data are LD, this method yields a mean value smaller than the individual value detection limit. The method is valid so long as a few data exceed the detection limit, although as a practical matter the confidence level is low if fewer than ten positive data points are involved with the fitting.

A question will remain as to whether two data distributions are involved, such that some or all of the LD values belong to a background distribution, with the higher values indicating impact from a source with intermittent loss of control. If all the positive data are very much above the detection limit, such a situation is indeed indicated. In other situations, the question cannot be answered solely from the data involved, although other independent data may be found to resolve the issue.

Group Comparisons. The primary purpose of most environmental surveillance is to determine the existence of and to quantify the effect by a facility on environmental radioactivity levels. When the existence of a local "background" level cannot be ruled out and potentially affected environmental media show measurable levels, a comparison may be made between a set of background or control measurements and a set of the same measurements in the potentially affected locations.

If estimates of central value and dispersion for each set have been obtained as discussed in the previous section, and tests for homogeneity are satisfactory, the data sets can be tested for equivalence. Commonly, this is directed toward determining if the central values of the two groups are different, but differences in variability are also informative and may be important. Graphical techniques may be useful, but the standard statistical tests for differences of means are usually relied upon.

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* e.g., $S_g = x_{0.8413}/x_{0.50}$ or $x_{.050}/x_{1587}$.

In actual practice such comparisons can be of dubious reliability when faced with data sets containing outliers, less than detection values, and non-Gaussian distributions, since most of the standard statistical techniques are not directly applicable in these situations. Moreover, the number of alternative procedures having good statistical properties are somewhat limited. Generally, the alternatives are nonparametric procedures.

The basic nonparametric tests available are the sign test, permutation tests, Mann-Whitney rank sum tests and Kolmogorov-Smirnov two sample test. These tests are all based on the relative rank ordering of the two data groups and do not assume any particular distributional shape for the groups. The specific procedures for applying the tests are not given here, but they are readily available in many elementary statistical tests. [14,15] These tests should not be used if actual distribution types are known because they are less sensitive than are specific distribution-based tests.

What about resistant alternatives? For the symmetric distributional shape, one possible alternative is to use the classical two sample t-test for differences in means (see above), replacing the usual arithmetic means and standard deviations used in the test with selected resistant alternatives such as medians. Presently, this type of approach is only beginning to be understood and no particular alternative can be recommended.

Summary of Recommended Data Treatment

	Dose Estimators(a)	Trend Indicators
Estimates of Precision	X	X
Corrections for Bias	X	
Sequential Plotting	X	X
Distribution Analysis	X	(b)
Group Analysis	X	(b)

(a) Required for critical exposure mode; desirable for other exceeding sampling criteria. Annual averages are required.

(b) Desirable for more significant measurements. Distribution analysis is required if group comparison is to be made.

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EFFECTIVE COMMUNICATION WITH THE PUBLIC

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Effective communication of radiological information to the public is one of the difficult tasks managers and scientists in the health physics field must face. This report explores this problem from the standpoints of an analysis of mass communication principles; enhancement of communication with the news media; and reporting environmental radiation data. Emphasis is placed on understanding the constraints of news media representatives by managers and scientists being interviewed. The goal is to provide a tool which will significantly increase their ability to communicate accurate and understandable radiological information to the public. (A list of references is included as an attachment to this report.)

(Communication; examples; media; reporting)

Purpose

To establish a plan for the professional practitioner to effectively communicate with the public.

Objectives

The objectives of this report are:

1. To educate management, scientific, and other professional staff on the importance of effective communication. This may involve a change in motivation and attitude on the part of the professional.
2. To enhance the ability of the professional to fulfill his responsibility to communicate with the public.
3. To translate radiation information into language meaningful to the public

Introduction

Few subjects are more of a mystery to the public than that of radiation. This lack of public understanding creates multiple problems such as:

1. Overreaction in regards to harmful physical effects it may produce.
2. Failure to place it in perspective with other hazards.
3. Vulnerability to exaggerated claims of both pro-nuclear and anti-nuclear individuals or organizations.
4. Inaccurate handling of radiation data and incidents by the news media.

In the light of these facts it behoves managers and scientists to inform themselves and their staff, on the need for effective communication with those not familiar with the field. In the past, this has not been given sufficient priority and time with the inevitable results of confusion, misunderstanding, fear and bewilderment so common today among the public in radiation matters. There is a current trend to correct this situation but it will take many years of dedicated effort to fill the vacuum and make up for past failures.

This report is designed to inform managers and scientists in the health physics field on the nature and structure of mass communication and how to relate to news media representatives and the public. The principle is that the more which is known of the news media methodology, problems and constraints, the more effectively communication may be accomplished.

However, this, for the most part, will be in vain unless it is used by people in the radiation protection field in their day-to-day contacts with the lay person, lay groups, the press and the electronic news media - hence, the importance of developing a deliberate plan to place this information in the hands of those who need to know.

Mass Communication Principles

Communication is the basic building block of human society. It is the process of transmitting meaning between individuals. Society, as we know it, could not very well exist in its absence.

Human beings, primitive to modern, have always relied upon person-to-person communication to transmit intentions, feelings, knowledge and experience.

Only in the past century or so have methods of communication really changed. The technological advances of the 20th century have worked many changes among and within the world's civilizations. People are no longer born to live and work and die in the same locale. Individuals travel frequently. They may change jobs, even whole vocations, several times. The individual in our society is constantly on the move and is constantly exposed to new acquaintances and new ideas.

The tremendous population growth and increased mobility of our civilization has resulted in a somewhat rapid decrease in personal interaction between individuals. The same technology which makes it possible for our society to function with such mobility is also utilized to provide rapid and mass dissemination of information to a constantly shifting and faceless constituency. Personal interaction between individuals has been replaced by impersonal means of communication in which the communicator and the individual with whom he wishes to communicate seldom, if ever, meet.

This impersonal means of communication among the constantly shifting members of our society takes many forms, but it can best be described simply as "mass communication."

This is a special kind of communication involving distinctive operating conditions. Health physics is a technical discipline utilizing highly specialized skills and knowledge. Such disciplines, of necessity, develop specialized terminology to provide their practitioners maximum communication capability. However, when technical information is mass communicated to the public in an unsimplified and unexplained form, it often serves only to confuse, to annoy, and to misinform.

Operating conditions which distinguish mass communication from more personal and simplified forms of human contact involve:

1. The nature of the communicator.
2. The communicating conditions.
3. The nature of the audience.

The nature of the communicator is especially important in mass communication because the communicator is usually not one individual, but rather a complex, organized entity involving an extensive division of labor and accompanied by a rather high degree of expense.

When the manager, scientist or technician in the health physics field communicates with the public by way of mass media, he or she will do well to keep the following in mind: Response to a media inquiry or initiation of an unsolicited news announcement in simple, clear and concise terms does not assure its delivery to the public in its original context. First, the individual to whom you communicate the information has not been educated and trained in your field and frequently has, at best, a superficial knowledge of your terminology and its meaning. So you are immediately involved with a problem in semantics. That individual writes down or records on tape and camera what you say. But that individual's perception of the meaning of your words may not resemble accepted meanings within the context of radiation physics, and the "story" presented the public, whether in writing, on tape or on film, will reflect the perceptions of the communicator rather than yours.

Second, the "story" will be handled by an editor, print or electronic, and its context will be influenced by a variety of factors not related to the meaning of the text. It may be shortened to fit the "new hole" in the newspaper or cut from a minute and a half to 45 seconds or less to conform with time requirements on the broadcast or telecast. In other words, the person who receives your original information must wade through a sea of semantics to put the story together. And a person who is competent in his field will then make the information fit the slot assigned it with little or no regard for the effect the deletion of a sentence or a paragraph may have on the audience or reader perception of the communicated information.

Third, the information will be passed through the hands of a headline writer or promotion writer whose job it is to read quickly through a multitude of information and write headlines or radio or television "promos" to attract the attention of the reader/viewer. By the time this individual goes to work on your information, it has passed through the perceptions and value judgments of at least two other persons. The headline or electronic media "lead in" may bear scant resemblance to the original information. Even here, space becomes a problem because the newspaper headline writer is assigned a type font and size which limits what words can be pieced together to form the headline in the allocated space.

Fourth, material picked up and transmitted by news wire services is often taken from newspapers, shortened to fit wire space requirements, and distributed with absolutely no contact with the principals involved. This type of operation is the nature of the beast for persons who work in the newswire field, but it can lead to extreme havoc when involved with a "breaking story" involving real or alleged contact with or exposure to radioactive materials.

Mass communication conditions are such that the audience is exposed to the communication for only a short period of time. Audience size normally prohibits interaction between the communicator and individual audience members. This means information of a highly complex nature must be presented to individual recipients by means of an impersonal, diversified, technological flash of lightning. The communication is public because it is addressed to no one in particular. It is rapid in that it is geared to reach large audiences simultaneously, and it is transient because it is intended for immediate use.

The mass communication audience is heterogeneous in that it is composed of an aggregation of individuals who occupy various positions in society with wide variations in age, sex, education and geographic location. The audience is anonymous because its individual members remain personally unknown to the communicator.

Complexities inherent in all phases of mass communications move the original communicator of information many stages away from the individual member of society with whom he or she is attempting to communicate.

It can be both functional and dysfunctional for the managers and scientists in the health physics field who are attempting to communicate information.

Mass communicated information is functional when it provides the individual recipient of the information with the capability to make intelligent personal decisions regarding the use of diagnostic or therapeutic equipment in today's technical environment which exposes one to various types of radiation. It is dysfunctional when it fails to properly inform and serves merely to frighten the individual to the extent that he or she may refuse examination or treatment using devices involving X-ray or other controlled radiation exposure useful in detecting and treating conditions which could lead to the individual's death.

It is fair to observe that today's health physicist, involved in a highly technical and complex field, is confronted with the task of conveying information to an anonymous, heterogeneous population by way of a communications medium that is so rapid, impersonal and diversified as to create a situation where the proverbial irresistible force strikes an immovable object. It may seem similar to looking at a road map only to find that there is no way to reach your desired destination from your present location.

Due to the complexity of both the information and the medium by which it must be conveyed, no guaranteed plan of action or program exists to assure that the modern manager or scientist will always be certain that his communications with the general population will reach their intended recipients undiluted and unchanged.

However, the following suggestions are submitted, in the belief that their utilization will increase the likelihood of success to a substantial degree.

1. Educate managers and scientists in your organization as to the nature of the medium through which they must communicate. Knowledge of problem areas within the mass communications concept can and will avert many of the unpleasant circumstances which confront health physics professionals on a daily basis.

2. Know what to expect. Do not expect the reporter to serve as your personal recording secretary. Do expect the reporter to take what you say with "a grain of salt" and to compare your comments with those of others who may or may not agree with what you say. Be as brief and as specific as possible. Try to avoid complex technical terms unless specifically accompanied by a simplified explanation.

3. Do make managers and scientists available to answer questions from newspersons if at all possible. Reporters do not like to depend entirely upon statements or material from the information or public relations office. Such information is frequently used only as the basis for a story. The reporter feels defeated if unable to talk in person with the principals of whatever activity is involved and will reflect this in his or her story.

4. Develop information useful in communication with media representatives in varied circumstances and on short notice.

Effective Communication with the News Media and the Public

Accident Situations

The health physics professional will find that during the course of his career many of his contacts with the news media will occur during accident or "incident" situations involving radioactive materials.

The nature of this contact may be direct at the site of an accident, or indirect, in providing technical assistance to a public information specialist who is carrying the lead in communications with the media.

The health physicist will find that he has two critical responsibilities during accidents involving nuclear materials. First, and most obvious, he will put to use his skills and training in attending the accident situation; secondly, he becomes a principal source of information for the news media and public.

Either the health physicist working alone or the public information specialist working at his side will immediately be besieged with questions of the following character: "Is there any radiation leakage? Is there any danger? Has anyone been exposed to radiation? How badly has the person been exposed? If the site is contaminated, will you have to evacuate?" And, for each one of these basic question can flow an almost endless chain of subquestions as the reporter attempts to comprehend the situation and translate that comprehension to a story.

Accidents involving nuclear material are unique in terms of information handling, presenting a distinct set of problems. It should be understood, however, that in terms of information handling, both the health physicist and the news media representatives share a common objective and that is accurate reporting of the accident. That the health physics professional often perceives the end product to be inaccurate, distorted or overplayed is a common reaction. The purpose of this section is to first attempt to explain why news coverage of radiation incidents is so zealous, then provide suggestions to the health physics professional on how to handle the flow of information to the news media during an incident to assure that he has done everything within his control to achieve accurate and fair reporting of the news.

The words "radiation accident" mean one thing to the health physics professional and another to the news reporter. To the former, it is an event to be expected during the course of one's career, providing the occasion to exercise his knowledge and expertise. To the news media, it is an event that as a rule, demands high attention, zealous, lengthy coverage and prominent display on the front page of a newspaper or high in the order of daily news covered by radio and television.

The difference in reaction is a matter of perspective. To some, radiation is perceived as completely understood, well-controlled, wisely-used by product of the nuclear age that is making invaluable contributions to the fields of medicine, industry, agriculture and research. On the other hand, radiation is also viewed as a mysterious force that completely evades all senses, that knows no obstacle, and can cause burns, disfigurement, cancer and bizarre biological mutations. In terms of dealing with the public as a whole and the news media in general, the latter perception, which drapes the subject of radiation in a veil of mystery, should be assumed as the prevailing attitude. There are additional suggestions as to the basis for this difference in perspective. One perspective suggests that since the world was formally introduced to atomic energy through its destructive profile, a conditioned, negative response, supported in part by feelings of guilt, is the inevitable result.

How to alter what is thought to be a general negative, uneasy attitude about radiation is the subject of endless discussion. It is generally thought that through education and gradually acquired familiarity with radiation, will come an informed rational, comfortable understanding and knowledge of the subject.

In the meantime, suffice it to say that "radiation" today is a word in our vocabulary that elicits a very strong, if not emotional, response; and from the viewpoint of the health physicist and information specialist involved in a radiation incident, a subject that must be treated with utmost care and sensitivity.

It bears repeating that unquestionably the most important role for the health physicist involved in an accident situation is resolution of the problem. On the other hand, because of the media's assured high level of interest in radiation incidents, a parallel responsibility exists to provide directly or through an information specialist prompt, factual information on the incident. To effect a reasonable balance between these two priorities requires a high degree of planning, preparation and coordination.

Following is a set of general guidelines to follow when dealing with the news media during a radiation accident:

1. Information necessary for the newsman to construct the "who, what, why, when, where, and how" of the accident should be provided as quickly as possible. In a significant accident, first attention should be directed to the so-called "electronic" media, i.e., radio and television plus the wire services, all of which have the capability of virtual "instantaneous" news reporting, compared with newspapers which operate on deadlines dictated by their mechanical reproduction processes.

When first arriving on the scene of an accident, it should be assumed that some media may already be on site, having obtained incomplete and often speculative information from emergency personnel that are unfamiliar with radioactive materials. Those newsmen should be intentionally sought out and the offer made to provide professional, clarifying and perhaps corrective information.

In those instances where a health physics professional along with other emergency personnel are dispatched to an accident site involving hours of travel time, consideration should be given to local news media representatives who, during the period of time required for travel, may arrive and depart the accident scene with fragmented, incomplete, or distorted information. It may be prudent in the interval to call the press, radio, television, and wire services in the immediate proximity of the accident giving them as much information as is currently available with a commitment to update and expand that information once the emergency personnel arrive on the scene. This call may involve no more than properly identifying the nature of the radioactive material involved in the incident, but even that simple confirmation can avoid early, erroneous news accounts that will later have to be corrected.

Rumors, chit-chat, the grapevine gossip and the like spread rapidly following an accident; and if the media feeds on this class of information, real trouble is the result and it may take hours to untangle and correct erroneous information. Often the success in correction is only partial.

2. Never try to hide or minimize the significance of a mishap. The true facts will emerge eventually; and it is better to seize the initiative by volunteering the information promptly, rather than be placed in an apparent defensive position which is extremely difficult to turn around, once established. Your relationship with the reporter will prove much more satisfactory if you, rather than he, initiated the dialogue. Your initiative demonstrates an attitude of openness and candor which will strengthen your position in the communication process.

3. Be sure of the facts before they are released, but do not let lack of detailed information serve as an excuse for not taking action. In the early minutes and sometimes hours after an accident, many facts cannot and will not be known. Newsmen should be so advised with the assurance that they will be given additional information as it becomes available. The first contact with a newsman may be no more than an advisory that an accident has occurred. Follow-

up information will fill in details as to the specific nature of the accident, the extent or seriousness of injury, nature of corrective measures to be undertaken, etc. Editors appreciate the early advisory for it enables them to plan their news "budget," make adjustments in reporting assignments, and contemplate news page makeup or newscast content, all of which can work in the interest of story accuracy. By making the initial contact as early as possible, the damaging effects of the rumor are also ameliorated.

A separate and distinct set of problems arises in the handling of information if the accident involves a radiation exposure victim. If the exposure is low, actual confirmation of the exposure and dose may be delayed while tests are being performed. If confirmation of an exposure slips from the day of the accident to the following day or longer, considerable difficulty will be experienced in dealing with newsmen who are accustomed to covering conventional accidents where injuries are known immediately. During the intervening hours while confirmation of a radiation exposure is being made, the individual dealing with the news media is in a very awkward position. Belief may exist that there has been exposure, but it has not been established as fact. If confirmation of the exposure is delayed, then the news media is often erroneously led to the suspicion that information is purposely being withheld. Care must be taken to dispel that suspicion by explaining the procedures involved in determining whether an exposure has occurred.

4. Avoid being drawn into making speculative statements based on hypothetical, "what if" kinds of questions. There may be rare occasions where such a question should be answered to avoid a reaction that something is being concealed. It is better to explain the rational for the reluctance to answer a question than to respond with a "no comment." It is difficult to conceive a situation where a simple "no comment" response would ever be appropriate.

5. Ideally there should only be one spokesman involved in providing information on an accident situation to the news media in the interest of achieving consistency. If a situation develops where more than one person is sharing the chore of providing information, each must keep the other fully briefed on the content of any discussions with the media. Frequently, an information specialist will carry the lead in a conversation with a member of the news media and a health physicist will be present (or a party to a telephone conversation) to provide backup for discussions bearing on the technical aspects of the accident.

6. Remember that any action taken at the site of an accident in the public domain can be misinterpreted. The taking of radiation readings by geiger counters, the taking of smear samples, the cordoning off of a given area and posting of warning signs are of course commonplace to the health physicist and other trained emergency personnel. However, to members of the public and press, such actions are likely to be a first time experience with the inherent risk that these novice observers can misunderstand their significance. Therefore, it is important to explain any overt precautionary or corrective steps taken in the full public view.

7. In the case of significant accidents which will likely come to wide attention, it is adviseable to take the time to make sure that local officials, i.e., mayor or city manager, are advised at an early opportunity. The news media will likely call them for reaction or comment and if they are officially briefed on the situation they will be able to respond from an informed position, aiding in the orderly, accurate dissemination of information.

Under the heading of advanced planning, a number of actions can be undertaken by health physics professionals that will make working under the stress of an accident situation less difficult.

First of all, all organizations, public or private, involved in handling or processing nuclear materials, should include in their emergency planning contingencies for handling inquiries from the press. A public information plan will include not only designation of the individual who will take the lead role in handling inquiries and his responsibilities, but also delineation of the responsibilities and obligation of other key organizational officials involved in handling the flow of information during an accident situation. The individual named to an information responsibility should not be so low in an organizational hierarchy that he must wade through various levels of management for the authority to make statements on behalf of the organization. As was mentioned earlier, information must move to the press quickly to avoid the damages that can be caused by the rumor mill.

Secondly, a continuing effort must be expended to educate the various "publics" which interact with a particular organization, facility or operation dealing in nuclear materials. This education effort should focus on explaining the nature of an organization's activities plus an outline of the facility's safety program to both prevent and to correct accident situations onsite and offsite. Such an education program can include an active press release program, the offer of press interviews with key plant personnel, arranging for plant tours, open houses, family days, etc., and maintaining a speaker's bureau. Health physicists can make a valuable contribution by offering to speak before civic clubs, schools, and various other community organizations on the nature of his profession with lay-level explanation of the nature of radiation, uses of radioactive materials in industry, research, medicine and agriculture, biological effects from exposure, etc. The obvious benefit of such a general educational effort is that should an accident occur, the negative effects of ignorance, misunderstanding fear and mystery can be reduced.

Health physicists can also make their expertise available to training programs presented for police, state patrol, firemen, ambulance attendants, civil defense personnel and the like. As previously stated, emergency personnel and news media often arrive at the scene of an accident simultaneously and the proficiency with which emergency personnel perform their duty reflects critically on both the situation and the associated flow of information to the news media.

Television Interview

1. Do your homework.

(a) Know your subject. Nothing builds confidence or enables you to keep control of an interview more than knowing your subject thoroughly.

(b) Get someone to play the devils advocate and put to you as many questions as they can think of that your interviewer may use. This will help keep you from being caught with an unexpected question which you can't answer on the spur of the moment.

2. For the actual interview:

(a) Use some make-up. A good appearance on the screen helps get a favorable reaction to what you say.

(b) Dress conservatively. Avoid patterns of clothing such as houndstooth or bold plaids which tend to jiggle on the screen. A pastel colored plain shirt will look better than a white one, but no loud fancy ones.

(c) The interviewer will usually discuss the subject, at least briefly, before starting the interview although he, or she, will not tell you the exact questions to be asked. This is not to try to trip you up but to make the interview appear spontaneous rather than rehearsed.

(d) Sit in a four legged chair. Never use a swivel. There is a subconscious tendency to squirm in a swivel chair giving the appearance of tension. If you're more comfortable standing, ask the interviewer to do the interview standing. That will usually be all right.

(e) Try to put the important points you want to make right away. Time devoted to your subject on the air will be very limited and the real impact of your message will stand a better chance of getting on the air if it is stated as quickly as possible.

(f) Without being curt or resorting to unnaturally clipped speech, make your statements as tight and concise as possible. With the brief time available on a newscast, each second is valuable.

(g) Do not be facetious. Appear friendly and confident-concerned but not worried or browbeaten.

(h) The interviewer is asking the question, not the camera. Therefore, look at him, the person asking the question, when answering.

(i) Do not call the interviewer by first name, even if you are well acquainted. This could be taken as a buddy-buddy relationship and some of the audience might feel you are being fed questions slanted to your advantage. If you feel you must address the interviewer, say Mr. __ or Ms. ___.

(j) If you don't know an answer, say so and that you'll try to get it to him promptly - and do so. This segment will likely be edited out.

An interview may be taped for five minutes or longer but it will usually be cut to 40 seconds or less. If editing time is tight, the editor will probably use the first portion and barely look at the rest. That's one reason it is important to get your main points made early.

When the interview is over, keep looking at the interviewer until he indicates he is through. The camera will probably continue rolling for a little time to provide a video picture while the announcer makes "voice over" comments in his own words.

The camera crew will often shoot some footage at different angles while you are asked to keep talking. This will also be used for voice over comments.

Frequently, only a very short segment will be your actual picture and voice. The remainder of the time will be voice over by the reporter. His comments are usually based on what you told him during pre-filming discussion.

And lastly, remember even though the interview is over, the reporter is still at liberty to use anything you say. So don't make careless remarks thinking that you are "off the record."

"Interview Bill of Rights"*

1. Rights of the Interviewee

(a) The right to an objective listening to the facts he presents.

(b) The right to an accurate representation of his position.

(c) The right to a fair and balanced context for his statements.

(d) The right to know in advance the general area of questioning and to have reasonable time for preparation.

(e) The right to reasonable flexibility as to when to have the interview. (Just as there are times when a reporter cannot be interrupted near a deadline, there are times when others cannot be interrupted).

(f) The right to expect the interviewer to have done some homework.

* (Editor & Publisher, May 28, 1977) by John Jamison, Director, Corporate Communications-NCNB.

(g) The right to withhold comment when there is good reason without having this translated as evading or "stonewalling," for example, information governed by SEC regulations, competitive secrets, matters in litigation or negotiation, information that could damage innocent persons.

(h) The right to an assumption of innocence until guilt is proven.

(i) The right to offer feedback to the reporter, especially to call attention to instances in which the story, in the honest opinion of the interviewee, missed the point or was in error - and to have this feedback received in good faith.

(j) The right to appropriate correction of substantial errors without further damage to the credibility or reputation of the interviewee's organization.

2. Rights of the Interviewer

(a) The right to access to an authoritative source of information on a timely basis.

(b) The right to candor, within the limits of propriety.

(c) The right to access to information and assistance on adverse stories as well as on favorable ones.

(d) The right to protection on a story the reporter has developed exclusively, until it has been published or until another reporter asks independently for the same information.

(e) The right not to be used by business for "free-advertising" on a purely commercial story.

(f) The right not to be reminded that advertising pays the reporter's salary.

(g) The right not to be held accountable for ill treatment by another reporter or another media at another time.

(h) The right to publish a story without showing it to the interviewee in advance.

(i) The right not to be asked to suppress legitimate news purely on the grounds that it would be embarrassing or damaging.

(j) The right not to be summoned to a news conference when a simple phone call, written statement, news release or interview would do just as well.

Reporting Environmental Radiation Data

Reporting environmental radiation data to the news media and/or the general public poses many problems for the professional health physicist. How can these data be communicated in a manner which will be understood and properly interpreted? How can over-emphasis on certain facets of a particular report be avoided? Listed below are some suggestions which will help:

- Avoid technical jargon and use of acronyms to the maximum extent possible. When technical terms must be used; define the terms in simple everyday words. If data is to be presented in a formal report, a summary, written in nontechnical language, should be a part of the report or included as an attachment.

- Compare radiation data with a familiar item such as diagnostic radiation X-rays.

- Report environmental radiation data in terms of concentrations or doses. If there are no statistical increases in environmental radiation levels then a statement such as "no increase in radiation detected above background levels" would suffice.

- If the problem is minimal so indicate in specific statements which are not likely to be misinterpreted.

- Avoid rambling dialogue on non-pertinent data as this may create more confusion and misunderstanding than education.

- Recognize that the individual seeking information in all probability knows little or nothing about radiation and may believe what he wants, including the "worst." The point is to keep language simple and avoid using words or phrases which can be exaggerated and blown out of proportion.

- Recognize that most news media representatives are operating on a very short time schedule and give the meaning of the environmental radiation data in clear concise statements at the outset of the interview. Double-talk or vague statements lead to suspicion and often erroneous interpretation by the media.

- If data is highly significant or technically complex, consideration should be given to holding a press conference to release the information in both written and verbal format. This provides more time for discussing the subject and data and answering questions at one time and place.

- Avoid language which may be ambiguous and lead to misunderstanding.

Conclusion

The material presented in the report demonstrates that managers and scientists must take time to educate themselves in communication principles and techniques if they expect to successfully transmit information to the public which will be understood and interpreted as intended. The time and effort expanded will be found to be worthwhile many times over, particularly in the field of radiation to which the public is currently so responsive.

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ENVIRONMENTAL RADIOLOGICAL SURVEILLANCE: MECHANISMS FOR INFORMATION EXCHANGE

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Subcommittee number 9's charter was to assess the adequacy of present means for environmental radiological information exchange and to propose new techniques if needed. Over two hundred health physicists throughout the country, who are involved in environmental surveillance, were contacted for their comments and suggestions. After these contacts were made, the discussions were analyzed in regard to existing communication mechanisms of other professional societies, government agencies, and information centers; these findings have been summarized and will be presented. It was concluded that strong support exists for creation of an Environmental Surveillance Newsletter and that this activity could conceivably fit into an Environmental Surveillance Section of the Health Physics Society. The desirability of the Health Physics Society's support for proposed symposiums, the format of the proposed newsletter, and possible mechanisms for support for these activities, will be reviewed.

(Environmental Data Bases; Environmental Information Centers; Environmental Surveillance Activities; Information Exchange)

Purpose of Subcommittee Number 9

This report assesses the need for and analyzes the various options available for information exchange mechanisms in the field of environmental radiation surveillance. In this field where technology and techniques are constantly being updated, it was the project steering committee's hypothesis that information flow could be inadequate. This committee's charter was to test this hypothesis.

Methodology of Approach

Contacts

The logical first step was to have the members of the committee contact various people throughout the country associated with radiological environmental surveillance activities. People associated with state and utility organizations were particularly singled out as it was felt that these individuals may be more in need of technological information updating; however, other industrial sites, EPA and NRC regional offices, universities, and national laboratory personnel were also contacted. The questions asked of the individuals interviewed were: (1) How do they get their information now? (2) Is it adequate? (3) Do they have any suggestions for improvement?

Summary of Comments

Just about everyone contacted had definite views concerning information exchange and were quite helpful. Due to the fact that close to 200 people were contacted, we cannot list all the comments; however, certain concepts were voiced repeatedly. The majority of contacts favored the creation of an Environmental Surveillance Newsletter over other mechanisms for exchange, such as an information center or other ideas. The contacts stated that in the environmental surveillance field they now try to contact someone else if they have a question. It is presently a "catch-as-catch-can" situation. Some random comments concerning a newsletter are stated below:

- "it should be oriented towards a practical grass roots approach"
- "information that is printed in the journal now is related to theory, not practical problems"
- "this information would be helpful, as I am just starting out in environmental monitoring"
- "would like to see nonroutine data covered in the newsletter, e.g., weapons fallout data"
- "would like to see new designs, methods, and instruments for environmental monitoring"
- "operational experience in environmental programs at other nuclear plants would be appreciated"
- "like to see suggested ways to simplify procedures and ways to compare results from various plants"
- "would like to see meetings, job opportunities, and training courses related to environmental surveillance listed in one place"
- "need a sounding board to ask questions related to radiological environmental surveillance"
- "... this is long overdue"

After sorting through the comments, the subcommittee agreed the newsletter should contain items concerning updated references and notices from regulatory agencies, letters to the editor (as a sounding board), meetings, training courses, and job opportunities and other items of interest. A draft of a sample newsletter containing some of the above items is contained in Appendix A.

Assessment of Existing Information Exchange Methods

At the same time that individuals were contacted concerning their opinions, the committee looked into existing information methods to ensure that what we would propose was not already existent through the government or professional society. In this endeavor, the Nuclear Regulatory Commission, Department of Energy, and Environmental Protection Agency were looked into. For the professional societies, American Industrial Hygiene Association, American Public Health Association, American Nuclear Society, Institute of Electrical and Electronic Engineers, and American Institute of Chemical Engineers were also contacted concerning environmental information exchange. In short, it was concluded that nothing exists at this time dealing with the exchange of information concerning radiological environmental information. The information bases that do exist are included in this section. Some data collected on environmental surveillance activities in other professional societies and existing information centers of interest are included in the sample newsletter in the following section.

Data bases and data banks exist in various sizes and forms. The collection of raw processed information is an essential tool for an environmental surveillance program. Table 1 is a summary of useful computerized systems. Government agencies, industries, trade associations and foundations keep data bases of historical environmental information. Table 2 describes selected data handling and information systems at the federal level.

The Environmental Protection Agency maintains a surveillance program for radioactivity levels called the Environmental Radiation Ambient Monitoring System (ERAMS). Table 3 is a summary of the current status and historical perspective of ERAMS.

Recommendations of Subcommittee 9

We encourage the formation of an Environmental Surveillance Section within the National Health Physics Society. Officers of the Section should be elected.

An information exchange newsletter should be part of the newly formed Section's activities. The editors for the newsletter will be appointed by the officers of the Section (with the editor's approval). The newsletter will be funded by the dues of the Section, and the printing and distribution of the newsletter should be contracted out to a private firm. One item the newsletter should contain is information that was included in the now defunct Public Health Service Radiation Data and Reports, since this was noted as an especially popular item with the people we contacted. We would prefer, however, that the Environmental Protection Agency renew this activity.

We also encourage a specialty certification in Environmental Surveillance, similar to the Reactor Health Physics Certification.

The Section should sponsor a symposium every other year or so. A special committee within the Section will be set up for this purpose.

Better public information on radiation effects should be made available.

A list of persons specializing in environmental surveillance should be made available to all members of the Health Physics Society.

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Table 1. Summarized List of Environmental Data Services[a,b]

	FUNCTIONS AND SERVICES	Literature Searches		Publications of Bibliographies	Microform Services	Publications	Abstracting and Indexing		Referral/Reference	Selective Dissemination of Information	Copying	Data Collection/ Storage and Retrieval	Data Analysis	Advisory/Consulting	State-of-the-Art Compilation	Interlibrary Loan	Bibliographic Research and Compilation	Translation	Computer Tapes	Available only to Government Contractors	Data Base	Information Center	Computer Program	Computer System	Data Bank
		Computer	Manual				Computer	Manual																	
1. American Agricultural Economics Documentation Center (USDA)		X		X	X	X													X			X			
2. CAIN System (Cataloging and Indexing), 1970-present				X																	X				
3. Center for Air Environment Studies; The Pennsylvania State University			X		X	X																X			
4. Air Pollution Technical Information Center (APTIC) (EPA)			X		X	X		X	X	X	X	X					X					X			
5. National Air Data Branch, Air Pollution Office (EPA)						X						X	X						X		X	X			
6. Air Quality Implementation Planning Program, Computer Program Tape																							X		
7. Projection Algorithm for Vehicular Emissions (PAVE-1)																							X		
8. Hazardous Air Pollutants Enforcement Management System (HAPEMS)																								X	
9. Central Abstracting and Indexing Service, American Petroleum Institute		X	X		X		X			X	X			X					X			X			
10. Franklin Institute Research Laboratories		X					X					X	X		X			X	X			X			
11. General Electric Company, Space and RESD Divisions		X	X				X			X		X	X	X		X						X			
12. Center for Urban Regionalism; Kent State University					X	X			X			X					X					X			
13. Textile Research Center; Illinois Institute of Technology		X	X			X				X		X	X	X								X			
14. Freshwater Institute Numeric Database (FIND)												X	X								X				
15. Environmental Information Retrieval On-Line (EPA)		X										X									X	X			
16. Tatsch Associates			X									X	X	X	X							X			
17. Eric Clearinghouse for Science, Mathematics, and Environmental Education; U.S. National Institute of Education							X					X	X	X		X						X			
18. Computerized Products and Services; Data Courier, Inc.						X	X												X			X			
19. Waterways Experiment Station; U.S. Army Corps of Engineers		X	X	X	X	X		X	X			X	X	X		X		X				X			
20. NASA Regional Center; Los Angeles						X						X									X				
21. American Society of Civil Engineers					X	X	X			X									X			X			
22. Smithsonian Science Information Exchange; Smithsonian Institution		X			X		X			X									X			X			
23. Center for Short-Lived Phenomena; Smithsonian Institution						X			X			X	X									X			
24. Conservation Library Center; Denver Public Library			X	X			X		X			X	X		X							X			
25. Ronald J. Scheidelman and Associates; Searchline		X	X							X			X									X			
26. Scientists' Institute for Public Information			X			X			X		X											X			
27. Ecology Forum, Inc.; Environmental Information Center		X	X		X	X	X		X	X	X	X	X				X		X			X			
28. Biosciences Information Services of Biological Abstracts	X									X		X										X			
29. Environmental Mutagen Information Center	X		X				X														X	X			
30. Biological Information Service							X			X				X								X			
31. Geographic Information Systems; Geographic Applications Program (USGS)												X		X					X			X			
32. Bibliography and Index to the Literature in the NBS Alloy Data Center							X															X			
33. Mineral Supply; U.S. Bureau of Mines		X			X							X	X				X					X			
34. Soil Data Storage and Retrieval Unit; Soil Conservation Service (USDA)	X											X	X						X		X	X			
35. Rock Mechanic Information Retrieval System; University of London	X						X			X		X							X		X	X			
36. ENDEX/OASIS NOAA Environmental Data Key	X											X									X				
37. Overview of the Water Quality Control Information System (STORET)												X									X				
38. Matrix of Environmental Residuals for Energy Systems (MERES)												X									X				
39. Institute for Scientific Information																									
40. National Weather Service River Forecast System																							X		
41. The Defense Documentation Center												X									X	X			
42. RECON (ERDA)	X											X								X	X			X	
43. Land Base–1973																					X				
44. Oil Shale Project, 1969 to Present																					X				
45. Battelle Energy Information Center (BEIC)		X							X												X	X			
46. Natural Resources Library: U.S. Department of the Interior										X							X	X				X			
47. Federal Aid in Fish and Wildlife; Denver Public Library	X			X			X					X										X			
48. Environmental Technical Information Center; Institute for Paper Chemistry	X	X							X	X		X									X	X			
49. Transportation Noise Research Information Service; National Academy of Sciences	X	X				X																		X	

Table 1. Summarized List of Environmental Data Services (cont'd)

	FUNCTIONS AND SERVICES	Literature Searches		Publications of Bibliographies	Microform Services	Publications	Abstracting and Indexing		Referral/Reference	Selective Dissemination of Information	Copying	Data Collection/ Storage and Retrieval	Data Analysis	Advisory/Consulting	State-of-the-Art Compilation	Interlibrary Loan	Bibliographic Research and Compilation	Translation	Computer Tapes	Available only to Government Contractors	Data Base	Information Center	Computer Program	Computer System	Data Bank
		Computer	Manual				Computer	Manual																	
50. Noise Information Retrieval System; Office of Noise Abatement and Control	X	X					X				X	X		X							X				
51. Toxicology Information Program; U.S. National Library of Medicine	X	X					X		X			X	X		X							X			
52. Analysis and Evaluation of Sources, Transport, Fate and Effects of Nuclear and Nonnuclear Contamination in the Biosphere		X						X				X	X	X	X					X				X	
53. Oil and Hazardous Materials; Battelle Memorial Institute		X										X	X	X							X				
54. Poison Control Toxicological Inquiry, 1956-1973												X												X	
55. Pesticides Data Bank (EPA)												X							X						X
56. Pesticides Information Center						X											X					X			
57. Office of Pesticide Programs (EPA)	X	X				X	X	X									X					X			
58. Analytical Methodology Information Center; Battelle Memorial Institute	X	X				X	X														X	X			
59. Mathematical Model for Outfall Plume																							X		
60. National Center for Resource Recovery, Inc.		X	X			X			X	X		X										X			
61. Simulation of the Time-Dependent Performance of the Activated Sludge Process Using the Digital Computer												X											X		
62. A Generalized Computer Model for Steady-State Performance of the Activated Sludge Process												X											X		
63. National Water Data System (USGS)				X						X			X	X						X					X
64. State of Washington Water Research Center; Washington State University				X					X	X		X					X						X		
65. Hydrological Information Storage and Retrieval System; Water Resources Research Institute							X						X	X	X					X			X		
66. Water Resources Scientific Information Center Network; U.S. Department of the Interior			X				X			X								X		X			X		
67. Environmental Systems Applications Center; Indiana University			X								X												X		
68. Main I: A System of Computerized Models for Calculating and Evaluating Municipal Water Requirements													X											X	
69. Main C: Computerized Methodology for Evaluation of Municipal Water Conservation Research Programs													X											X	
70. Forecasting Municipal Water Requirements													X											X	
71. Mathematical Simulation of Ammonia Stripping Towers for Wastewater Treatment													X											X	
72. Dam 2, Fortran IV Computer Program													X											X	
73. Project Formulation–Hydrology, Fortran IV Computer Program													X											X	
74. Computer Program for Preliminary Design of Wastewater Treatment Systems													X											X	
75. Preliminary Design and Simulation of Conventional Wastewater Renovation Systems Using the Digital Computer													X											X	
76. Wastewater Treatment Plant Cost Estimating Program													X											X	
77. Watershed Conservation and Development Master File, 1973													X												X
78. Water Surface Profile Program													X											X	
79. Mathematical Model of Natural Draft, Wet Cooling Towers													X											X	

Table 1. Summarized List of Environmental Data Services (cont'd)

FUNCTIONS AND SERVICES	Literature Searches		Publications of Bibliographies	Microform Services	Publications	Abstracting and Indexing		Referral/Reference	Selective Dissemination of Information	Copying	Data Collection/ Storage and Retrieval	Data Analysis	Advisory/Consulting	State-of-the-Art Compilation	Interlibrary Loan	Bibliographic Research and Compilation	Translation	Computer Tapes	Available only to Government Contractors	Data Base	Information Center	Computer Program	Computer System	Data Bank
	Computer	Manual				Computer	Manual																	
80. Data Bases: Solid Earth and Solar-Terrestrial Environmental Data										X		X	X							X	X			
81. Data Bases: Oceanography						X						X	X								X			
82. Analyses of Natural Gases												X												X
83. Data Bases: Climatology						X				X		X								X	X			
84. Energy and Environmental Systems Division (ALC)												X				X				X	X			
85. NUS Corporation Technical Library	X		X						X												X			
86. SDC/POLLUTION	X						X					X								X				
87. SDC/COMPENDEX	X						X					X								X				
88. American Geological Institute						X	X					X								X				
89. National Technical Information Service (NTIS)	X				X		X					X								X	X			
90. Chemical Abstracts Service, Division of American Chemical Society					X	X	X					X								X	X			
91. Nuclear Science Abstracts (ERDA)						X	X											X						

[a] Green, et al., 1976.
[b] Golden, et al., 1979.

Table 2. Data Handling and Information Systems at the Federal Level[a,b]

Sponsor	Air		Water		Comprehensive Environmental Data	
U.S. Environmental Protection Agency	AEROS	– Aerometric and Emissions Reporting Systems	STORET	– Storage and Retrieval of Water Quality Data	NERC	– National Environmental Research Center
	NEDS	– National Emissions Data System	ENVIRON	– Environmental Information Retrieval On-Line	PRES	– Program Review and Evaluation
						Environmental Impact Statement System
	SAROAD	– Storage and Retrieval of Aeromatric Data	GPSF	– General Point Source File		
	QAMIS	– Quality of Aeromatic Data	NEI	– National Estuarine Inventory		
	SOTDAT	– Source Test Data Storage	Water Quality Standards			
	HATREMS	– Hazardous and Trace Substance Inventory System				
	SIP	– State Implementation Plan				
	EDS	– Energy Data System				
	FPC-67	– Cumulative FPC Form 67 Data System				
	APTIC	– Air Pollution Technical Information Center				
	UNAMAP	– Users Network for Applied Modeling of Air Pollution				
U.S. National Oceanic and Atmospheric Administration			ENDEX	– Environmental Data Index	EDBD	– Environmental Data Base Directory
			EDS	– Environmental Data Service	ESIC	– Environmental Science Information Center
U.S. Geological Survey, Water Resources Division			OWDC	– Office of Water Data Coordination		
			NWDS	– National Water Data System		
U.S. Department of the Interior			WRSIC	– Water Resources Scientific Information Center Network		

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[a] Fennelly, et al., 1976.
[b] Golden, et al., 1979.

Table 3. EPA's Environmental Radiation Ambient Monitoring System Current Status[i]

Component	Number of Sampling Sites	Sampling Frequency	Analyses Performed	Frequency of Analysis	Previous Network	Initially Established
Air Monitoring Program						
Gross Radioactivity and Deposition	20 Active 54 Standby[a]	Semiweekly	Gross β[b] Gamma Scan[c]	Semiweekly	Radiation alert network	1956
Deposition	20 Active 54 Standby[a]	As rain occurs	Gross β Gamma Scan[d]	As rain occurs As rain occurs	Radiation alert network	1956
			Tritium	Monthly composite		1967
			^{238,239}Pu ^{234,235}U	March-May Composite		1974
Plutonium and Uranium in Air	20	Semiweekly	^{238,239}Pu ^{234,235}U	Quarterly[c] Quarterly[e]	Plutonium in airborne Particulates	1965
^{85}Kr in Air	12	Semiannually	^{85}Kr	Semiannually	No network, but individual measurements for 1962	1973
Water Analysis and Sampling Program						
Surface Water	55	Quarterly	Tritium Gamma Scan	Quarterly[e] Annually[e]	Tritium surveillance system	1964
Drinking Water	76	Quarterly	Tritium Gross α Gross β Gamma Scan ^{226}Ra ^{90}Sr	Quarterly Annually[e] Annually[e] Annually[e] Annually[f] Annually[g]		1970
	20	Quarterly	^{238,239}Pu ^{234,235}U	Annually[e] Annually[e]	None	
Interstate Carrier System	658 ~220/year	Triannually	Gross α Gross β ^{90}Sr ^{226}Ra	Triannually	Interstate Carrier Drinking Water Project	1960
Milk Analysis Program						
Pasteurized Milk	65	Monthly	Gamma Spectrometry[h] ^{89,90}Sr Tritium	Monthly Annually[c]	Pasteurized milk network	1960
Special Milk Analysis	9	Monthly	^{14}C	Annually[e]	^{14}C	1965
Human Organ Program						
Bone Analysis	Varies	Annually	Stable Calcium ^{90}Sr	Annually Annually	Human bone network	1961

[a] Activate if contaminating event occurs (*e.g.*, atmospheric nuclear test in the Northern Hemisphere).
[b] Field estimate and subsequent laboratory determination.
[c] If gross beta is greater than 10 pCi/m^3.
[d] If deposition exceeds gross beta of 15nCi/m^3.
[e] Composite sample analyzed.
[f] If gross alpha level exceeds 3 pCi/liter.
[g] If gross beta level exceeds 10 pCi/liter.
[h] For ^{131}I, ^{137}Cs, ^{140}Ba, and K.
[i] Golden, et al., 1979.

Sample Newsletter

ENVIRONMENTAL
RADIATION
SURVEILLANCE

FORUM

A MECHANISM FOR INFORMATION EXCHANGE

Vol. 1, No. 1 H.P.S. Subcommittee Number 9 Fall 1979

Editor-in-Chief

Editors

STATES CONTACTED - OPINION SURVEY REGARDING ENVIRONMENTAL RADIATION SURVEILLANCE

Two hundred individuals involved in some aspect of environmental radiation surveillance were contacted by Subcommittee #9 members in order to obtain their opinions on how to best obtain and interpret environmental monitoring information. State government representatives, reactor and fuel cycle managers, EPA regional officers, and NRC field persons were among those polled with questions regarding the adequacy of current data resources and present information exchange methods.

The majority of respondents felt that improvements in communication were badly needed and thought that a periodical newsletter could answer many of their needs. Many contacts indicated that field persons are forced to rely too greatly on the "grapevine" for knowledge and support in their monitoring efforts and subsequently do not have equal access to current techniques and methods.

Comments most frequently submitted by respondents include: a) new reports and pertinent notices should be made available through a readily accessible medium, b) a nuts-and-bolts field-oriented approach to current practices would be most useful, c) evaluation of environmental radiation surveillance (ERS) instruments should be shared, and d) methodologies of data analyses should be openly reviewed.

WATCH THIS SPACE..........

Watch this space for future articles on topics such as

What are other professional societies doing in the field of radiation surveillance.....

Should a new section be formed? An invitation for comments.....

What's new in information retrieval resources.....

The need for QA.....

What is the utility viewpoint.....

Should the Subcommittee conduct a symposium.....

Guest editorials submitted by state reps, utilities, feds, etc.....

Would you like to present a poster session at a non-HPS meeting explaining the function of HPS radiation surveillance interests.....

WATSON GIVES AD HOC COMMITTEE REPORT

In 1977 the HPS established an ad hoc committee with a multipurpose mission. Upgrading Environmental Radiation Data was the Committee's designated task and Chairman James E. Watson, Jr. (Dept. Env. Sci. and Eng., Univ. of North Carolina) recognized the charge as one requiring input from persons representing many areas of science and policy. Watson's ad hoc committee subsequently identified nine priority areas of interest, established subcommittee status for the projects, and recruited subcommittee members from industries, academics, state governments, and federal agencies including DOE, EPA, NBS, NRC and TVA.

Watson and each of the project leaders will present the results of their subcommittee efforts at a special session of the 1979 Annual Meeting of the HPS (Philadelphia, PA). The titles of the nine subcommittee projects and the committee member serving as project manager in each case are identified as follows:

(1) Objectives of Environmental Radiation Monitoring, (E.F. Conti), three types of monitoring are especially considered by the group-ambient, operational, and special investigation-type efforts.

(2) Definition of Critical Pathways and Radionuclides for Population Radiation Exposure at Nuclear Power Stations, (B. Kahn), power plant design objectives are compared to evaluation techniques and applied to predicted effluent fractions.

(3) Propagation of Uncertainty Analysis in Environmental Pathway Dose Modeling, (W. Britz), the applicability of pathway dose models is considered as a function of the reliability of individual measurement parameters.

(4) Detection of Changes in Environmental Radiation Levels Due to Nuclear Power Plant Operations, (G.G. Eichholz), variations in normal environmental radiation background must be quickly identified as a result from operational or extraneous activities.

(5) Effective Communication with the Public, (R. Payne) communication that will significantly improve the health physicist's ability to provide understandable radiological information to the public (via the news media) are suggested.

(6) Statistical Methods for Environmental Radiation Data Interpretations, (D.A. Waite), experimental designs, sample selection, data analysis, establishment of reliable baselines, handling variables in sampling equations and choices of alternative techniques are considered.

(7) Reporting of Environmental Radiation Measurement Data, (R. Colle), standardization of data reporting in terms of units, significant figures, and measurement uncertainty is advised and methods for instituting uniform reporting procedures have been devised.

(8) Quality Assurance for Environmental Monitoring Programs, (C.G. Sanderson), comprehensive QA programs that appreciate administrative input as well as sample integrity are analyzed and guidelines for such are provided.

(9) Mechanisms for Environmental Radiation Information Exchange, (T.W. Oakes), utilizing solicited input from field workers in environmental radiation surveillance, techniques of improved information exchange, including the issuance of timely newsletters, can be initiated by members of this subcommittee.

ENVIRONMENTAL SURVEILLANCE ACTIVITIES IN OTHER SOCIETIES

The American Nuclear Society sponsors symposia of interest to workers in environmental surveillance activities at it annual meetings and at topical meetings. In the 25th Annual Meeting at Atlanta, GA, June 3-7, 1979, symposia on "Environmental Monitoring and Measurement Techniques," "Environmental Transport Mechanisms," Waste Management," etc. were conducted.

The Institute of Electrical and Electronic Engineers regularly sponsor Nuclear Science Symposia which include papers on instruments and methodology for environmental radiation measurement.

The Nuclear Technology Section of the American Chemical Society sponsors symposia on various aspects of radioactivity measurements at its annual meetings. At the 178th ACS National Meeting, September 10-14, 1979 at Washington, D.C., symposia on "Waste Chemistry of the Nuclear Fuel Cycle as it Relates to Health and Safety," "Recent Developments in Biological and Chemical Research with Short-Lived Radioisotopes," and "Radionuclides in Earth and Space Sciences" were conducted.

The Annual Bioassay Conference is presented in the fall of each year. The 23rd Annual Meeting is scheduled for October, 1979, in Las Vegas, Nevada. Many of these papers will be of interest to environmental surveillance workers.

The 23rd Annual Conference on Analytical Chemistry in Energy Technology was conducted on October 9-11, 1979 at Gatlinburg, Tennessee. This annual conference is sponsored by the Analytical Chemistry Division of Oak Ridge National Laboratory. The theme of this year's conference was "Progress and Problems in Radioactive Analysis."

Future issues of the FORUM will update environmental surveillance activities of the aforementioned organizations and will include additional information from domestic and international conferences.

INFORMATION CENTERS OF INTEREST TO ENVIRONMENTAL SURVEILLANCE ACTIVITIES

Information centers play a valuable role in many aspects of environmental surveillance programs. Information centers are conducted at many organizations throughout the United States, and a large number of such centers and related projects are resident at Oak Ridge National Laboratory. A 65-page brochure, "ORNL Technical Information Center Program," (October, 1978) describes the current extent and availability of such information. The brochure is available from the Office of Information Centers, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, TN, 37830.

Some of the more than two dozen centers are:

Ecological Sciences Information Center: Data bases to support bioenvironmental research specializing in nuclear and fossil energy and environmental effects of electric power generation.

Nevada Applied Ecology Information Center: Major emphasis on the environmental aspects of plutonium and other transuranics.

Health and Environmental Studies Program: Comprehensive, multidisciplinary state-of-the-knowledge monographs and assessment reports on the effects of environmental pollutants.

Ecosystem Analysis Data Center: Respository for data generated by the Eastern Deciduous Forest Biome Program; regional assessment and ecosystem studies.

Geoecology Project: Data describing the spatial and temporal distributory environmental resources for analysis of regional and national energy-related problems.

National Inventory of Biological Monitoring Programs: A centralized and coordinated system for accessing biological monitoring information.

Nuclear Safety Information Center: National center for nuclear safety information; publication of Nuclear Safety.

EMPLOYMENT OPPORTUNITIES

This space will be devoted to current job opportunities in the broad areas of health physics, environmental surveillance, etc. Employees having current needs for specialists in these areas may send announcements of such openings to the editors for inclusion in two successive issues of the FORUM. No attempt at providing a clearing-house will be made. Only announcements for direct contact between employer-employee will be included. As an example of the format a current opening from the USNRC (June 1979) Engineering and Scientific Employment Opportunities is quoted:

Title: Health Physicist GS-9/11

Duties: Participates in the development of occupational health protection standards, including regulations, guides and topical reports. Performs calculations and analyses to develop or assist in the development of standards for occupational health protection, particularly those needed in the preparation of value-impact analyses.

Qualifications: Graduate level training in health physics, or B.S. level, plus specialized work experience. Submit Standard Form 171, "Personal Qualification Statement," available at most Federal Offices to: U.S. Nuclear Regulatory Commission Division of Organization and Personnel Recruitment Branch, Washington, D.C. 20555.

SELECT PAPERS FOR YOUR REFERENCE

This section will include a listing of current journal articles, conference proceedings, regulatory guides, and general literature references of interest to the environmental radiation surveillance field. Three members of the editorial staff will routinely scan a list of journals and other information sources to select the titles to be included in this section. A listing of the literature included in the search will be published once or twice per year, and additions can be made upon recommendation of the readership. The format of literature citation will be similar to the example shown: "Environmental Radiological Surveillance in Perspective: The Relative Importance of Environmental Media as a Function of Effluent Pathway and Radionuclides," D.H. Denham, Health Physics, March 1979, pp. 273-282.

SELECTED REFERENCE PUBLICATIONS

This section will include references to proceedings of meetings and symposia of interest to environmental surveillance workers. Special publications of IAEA, ANS, and NCRP will be listed. In some cases, editorial comments will be added to call attention to certain publications useful as desk references. Examples of two recent publications are:

Instrumental and Monitoring Methods for Radiation Protection, 1978, NCRP Report Number 57, pp. 177. (Ed: This report supersedes NCRP Report No. 10, "Radiological Monitoring Methods and Instruments.")

A Handbook of Radioactivity Measurement Procedures, 1978, NCRP Report Number 58, pp. 506. (Ed: This report updates and extends the 1961 NCRP Report Number 28, "A Manual of Radioactivity Procedures." It is a useful desk reference and contains a 135 page appendix of nuclear-decay data for some 200 radioactive nuclides of interest in medical practice research, health physics, industry, nuclear power, environmental impact studies, and as reference standards.)

ANNOUNCEMENTS OF MEETINGS, SYMPOSIA, AND COURSES

This section will include announcements of interest to environmental surveillance workers concerning future meetings, courses, or symposisms according to the format below:

19-23 Nov. 1979

"The Second Asian Regional Congress on Radiation Protection," IRPA Manila, Phillipines. Contact: Dr. Delia T. Anstalio, Ministry of Health, Rizal Ave. Sta. Cruz, Manila, Phillipines.

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